Influence of Types of Chemical Admixture and Their Dosages on Properties of Ready Mix Concrete

by

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Recommendation of the Board of Examiners

The thesis titled "**Influence of Types of Chemical Admixture and Their Dosages on Properties of Ready Mix Concrete**" submitted by Tanvir Ahmed, Student ID 125602 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 dedicate this thesis to my parents, my grandparents, my wife and my teachers.

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Abstract

An experimental investigation was carried out to study the effects of types of chemical admixture, increased dosage of admixture, two-stage dosage of admixture, sand to total aggregate volume ratio (s/a), cement content (cc) and fresh concrete temperature on fresh and hardened properties of ready mix concrete. For conducting the investigation, six different types of concrete mixtures were prepared using different types of chemical admixtures, different dosages of admixtures; varying s/a ratio (0.4 and 0.45), cement content (340 kg/m^3 and 380 kg/m^3); and controlling temperature of fresh concrete. Chemical admixtures such as water reducer based on lignosulphonate; and superplasticizers based on naphthalene sulphonate, organic polymer, second generation polycarboxylic ether, modified polycarboxylic ether, sulphonated naphthalene polymer and synthetic polymer were collected from the local market. Each mixture was subjected to prolonged mixing; slump readings were recorded at 15 minutes intervals to assess the fresh behavior of concrete. A total of 297 cylindrical concrete specimens of diameter 100 mm and length 200 mm were made with the mixtures for assessing the hardened properties of concrete. The specimens were tested for compressive strength, splitting tensile strength, Young's modulus and ultrasonic pulse velocity (UPV).

Results indicate that sulphonated naphthalene polymer based superplasticizer and second generation polycarboxylic ether based superplasticizer show best performances in both fresh and hardened states of concrete. The compressive strength of concrete increases with the increase of admixture dosage, when the dosage of admixture is within the range recommended by manufacturer. Applying dosage of chemical admixture in two stages imparts better workability to concrete than applying the same dosage of admixture at the beginning of mixing process. UPV through concrete with admixture is higher compared to UPV through concrete without admixture. For a given water to cement ratio (W/C), workability of concrete increases with the increase of cement content. Workability of superplasticized concrete can be improved by reducing the temperature of fresh concrete during the mixing process.

CHAPTER 1: INTRODUCTION

1.1 General

In the construction industry, the demand of ready mix concrete (RMC) is increasing rapidly day by day. The primary reasons behind this are: convenience of using RMC in high rise structures, shortage of space at construction site, saving of time related to the preparation of concrete on site and better quality of RMC. In cities like Dhaka, the time required to travel from the RMC plant to construction site is very high, because of severe traffic congestions, especially during weekdays. To keep concrete workable for such a long time period is very challenging. Moreover, high ambient temperature in summer makes the situation worse, since high temperature adversely affects the workability of fresh concrete (Mehta and Monteiro, 2006). Therefore, high workability has become one of the most desired and essential properties of RMC in Dhaka city. A conventional practice to improve workability of concrete is to add water in the concrete mix. But with the increase of water to cement ratio (W/C), the compressive strength of concrete reduces significantly (Wassermann et al., 2009, Dhir et al., 2004, Schulze, 1999). So to overcome this problem, in recent years, RMC manufacturers in Dhaka city have started using chemical admixture as a fourth ingredient in concrete apart from cement, aggregates and water. Chemical admixtures allow RMC to achieve high workability without compromising its quality at hardened state. The workability of RMC can also be improved by reducing the temperature of concrete mix and the temperature of mixing environment.

In light of the above discussion, it is necessary to conduct a comparative analysis among different chemical admixtures available in the local market and to identify their effects on fresh and hardened states of concrete. Therefore, this study plans to investigate the effects of chemical admixtures of different chemical properties on fresh and hardened properties of concrete. The effects of dosage of chemical admixture and repeated dosages of admixture on the properties of concrete are also aimed to be evaluated. Another objective of this study is to analyze the effects of sand to total aggregate volume ratio and cement content on properties of concrete made with chemical admixture. The effects of reducing fresh concrete temperature on the fresh and hardened properties of concrete are planned to be investigated as well.

Throughout the experimental investigation, slump tests were performed for different concrete samples to study their fresh properties (e.g. workability); different destructive and non-destructive tests were performed to assess their hardened properties (e.g. compressive strength, splitting tensile strength, Young's modulus and ultrasonic pulse velocity). The results obtained from ultrasonic pulse velocity (UPV) test were correlated with compressive strength of concrete. Correlations between splitting tensile strength and compressive strength, and Young's modulus and compressive strength were also developed on the basis of the experimental data.

1.2 Background

Ever since the introduction of chemical admixtures in the construction industry many studies have been carried out to understand the effects of chemical admixtures on fresh and hardened states of concrete. Researchers have unanimously agreed that, chemical admixture in general help improving the workability of fresh concrete. However, the understanding of the effects of admixture types, effects of admixture dosages as well as the effects of repeated dosages of admixture is not beyond controversy. For instance, Mohammed and Hamada (2003), Rao and Kiran (2015), Alsadey (2012) and Shah et al. (2014) observed that, if the water to cement ratio is kept unchanged the inclusion of superplasticizer in concrete increases the compressive strength, tensile strength and Young's modulus of concrete. On the other hand, Al-Kadhimi et al. (1987) and Jerath and Yamane (1987) concluded that, for constant W/C ratio addition of superplasticizer in concrete causes reduction in the compressive strength, tensile strength and Young's modulus. Similarly, literature gives contradictory data regarding the effects of increased dosage of chemical admixture, repeated dosages of chemical admixture and prolonged mixing of superplasticized concrete on hardened properties of concrete. Therefore, the present study aims to perform an experimental investigation to address these controversies.

Moreover, in Bangladesh, the demand of ready mix concrete (RMC) is increasing rapidly. High workability is one of the key parameters of good quality RMC. Therefore, selection of good quality chemical admixture is essential. Again, selection of proper dosage of admixture and proper time for mixing the admixture with concrete mix can also contribute to achieving good workability. With this view, the present study has been planned to conduct a comparative analysis among different types of admixtures available in the local market so as to identify the best admixture type. The performances of fresh and hardened concretes made with different types and dosages of admixtures in comparison to the performance of conventional concrete have also been aimed to assess.

1.3 Objectives of the Study

The objectives of this study are as follows:

1. to evaluate the fresh and hardened properties of concrete made with different types and dosages of chemical admixture;
2. to understand the effects of variation of s/a ratio and cement content on properties of concrete with chemical admixture;
3. to study the effects of reducing fresh concrete temperature on fresh and hardened properties of concrete made with chemical admixture; and
4. to understand the relationships between splitting tensile strength and compressive strength; Young's modulus and compressive strength; and compressive strength and ultrasonic pulse velocity (UPV) of superplasticized concrete.

1.4 Methodology

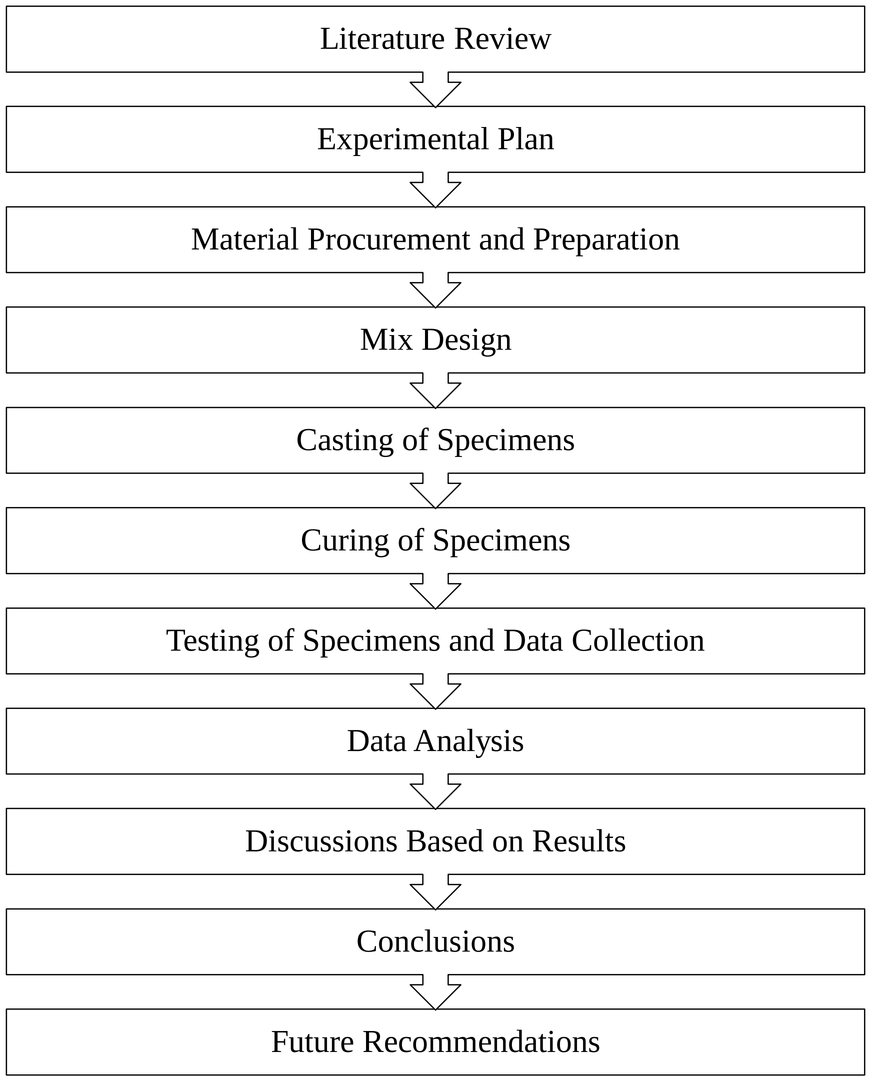

Fig. 1.1. Research flow diagram

The steps followed to conduct this study have been shown in sequential order in **Fig. 1.1**. In this study, an experimental investigation was planned to carry out, in order to address the effects of different types of chemical admixture and their dosages on fresh and hardened properties of ready mix concrete. Prior to starting the experimental process, a detailed literature review was done to demarcate the scope of the work. After defining the scope of the work, an experimental plan was set up.

For investigation, nine different chemical admixtures were collected from the local market. All the chemical admixtures satisfy the requirements specified by ASTM C 494. Crushed stones with maximum size of 19.0 mm were used as coarse aggregates. Locally available Sylhet sand was used as fine aggregates. The gradations of both the aggregates conform to the requirements specified by ASTM C 33. The aggregates were tested for specific gravity, absorption capacity, abrasion resistance and unit weight. Both the aggregates were brought to saturated surface dry (SSD) condition before the preparation of concrete mixture. CEM Type II B–M cement was used as binding material.

Mix design was done for each concrete mixture (i.e. material requirement of 1 m^3 of each concrete mixture was calculated). Different concrete mixtures were prepared for different types and dosages of admixtures varying s/a ratio, cement content and fresh concrete temperature. The mixtures were subjected to prolonged mixing. Slump tests were performed for each concrete mixture to understand the fresh concrete behavior. Slump tests were done according to the guidelines of ASTM C 143.

A total number of 297 cylindrical concrete specimens of diameter 100 mm and length 200 mm were made for the assessment of hardened properties. Cylinders were made according to the guidelines of ASTM C 31. The curing of specimens was done according to ASTM C 192.

The specimens were tested for splitting tensile strength at the age of 28 days, and compressive strength, Young's modulus and ultrasonic pulse velocity (UPV) at the age of 7 days, 28 days, and 90 days.

Test results were analyzed to identify the influence of types of chemical admixture, increased dosages of admixtures, two-stage dosage of admixtures, s/a ratio, cement content, temperature of fresh concrete on fresh and hardened properties of concrete.

Based on the obtained results a number of conclusions have been drawn. Depending upon the limitations of present study, a guideline for conducting future studies has also been recommended.

1.5 Layout of the Thesis

Chapter 1 thoroughly discusses the background and objectives of this study. **Chapter 2** discusses the influence of chemical admixtures on concrete properties based on literature review. It also discusses the effects of admixture dosage, repeated dosages of admixture, s/a ratio, cement content, fresh concrete temperature on fresh and hardened behaviors of concrete based on the findings of recent researches. **Chapter 3** presents the detailed procedure of the preparation of concrete mixture, as well as the cases investigated in this study. In addition, it outlines the actual mix designs of concrete mixtures. 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 states. The results obtained from the tests conducted 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. Several relationships between concrete properties are also presented in this chapter. **Chapter 5** presents 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 about different types of chemical admixture in general. The chapter also describes about the effectiveness of different admixtures on the basis of past studies. Effects of admixture dosage and application of admixture in stages on the fresh and hardened properties of concrete are discussed. Effects of sand to total aggregate volume ratio and temperature of fresh concrete on the fresh and hardened properties of ready mixed concrete are also discussed based on literature review.

2.2 Why Chemical Admixture is Used in Concrete?

When concrete is fresh, it is desirable to be malleable or workable. But sometimes, due to scorching conditions at site, desirable workability cannot be maintained (Shah et al., 2014). Retempering with water is a common practice to restore the initial workability. The amount of water required to produce a given slump increases with the extended mixing time. The addition of water without proper adjustments in mix proportions adversely affects the ultimate quality of concrete (Gedik, 1998). Abrams (1919) proposed that, when concrete is full compacted, its 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, 1995). Researchers have agreed that, with increase in the W/C ratio, the workability of fresh concrete increases, but the strength of hardened concrete gradually reduces. 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 was confirmed by later research done 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. 2.1**. Similar conclusion was also drawn by Wassermann et al. (2009), Dhir et al. (2004), Schulze (1999), Felekoğlu et al. (2007), Mehta and Monteiro (2006).

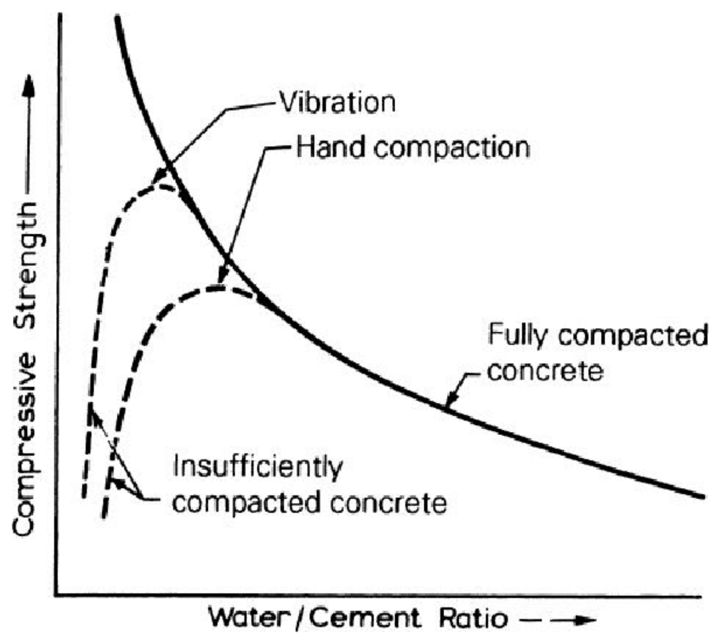

Fig. 2.1. Relationship between compressive strength and W/C ratio (Mindess et al., 2003)

So, this can be understood from previous studies that, although increased W/C help improving the workability of concrete, compressive strength of concrete decreases significantly with the increase of W/C ratio. The problem can be resolved using chemical admixtures in concrete without increasing the W/C ratio.

According to ACI 116R (2000), admixture can be defined as “a material other than water, aggregates, cementitious materials, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing”

Chemical admixtures are used in concrete mixtures for three different purposes or in a combination of these (Collepardi, 1995):

(i) to increase workability without changing the mix composition in order to enhance placing characteristics of concrete;
(ii) to reduce the mixing water and the water-cement ratio (W/C) in order to increase strength and improve durability at a given workability; and
(iii) to reduce both water and cement at a given workability in order to save cement and reduce creep, shrinkage and thermal strains caused by heat of cement hydration.

2.3 Types of Chemical Admixture

Two major types of chemical admixture that can increase workability of fresh concrete are plasticizers and superplasticizers. They may have water reducing or retarding or both characteristics.

According to ASTM C 494 – 10, there are seven different types of chemical admixtures as shown in **Table 2.1**. Amongst these, Types – A, B, D are plasticizers and F, G are superplasticizers. The other two types (i.e. Types – C and E) are accelerators. Types C and E do not contribute to achieving workability of fresh concrete, on the contrary they speed up the setting process.

Table 2.1. ASTM C 494 chemical admixture types

ASTM C 494 Types	Behavior
A	Water reducing
B	Retarding
C	Accelerating
D	Water reducing and retarding
E	Water reducing and accelerating
F	High range water reducing or superplasticising
G	High range water reducing and retarding, or superplasticising

2.3.1 Retarders

A delay in the setting of the cement paste can be achieved by the addition of a retarding admixture (ASTM Type B) to the mix. Retarding action is exhibited by sugar, carbohydrate derivatives, soluble zinc salts, soluble borates and some other salts (Ramachandran, 1993); methanol is also a possible retarder (Ramachandran and Beaudoin, 1987). Ashworth (1965) observed that, in a controlled environment, a small quantity of sugar (about 0.05 per cent of the mass of cement) acts as an acceptable retarder: the delay in setting of concrete is about 4 hours. The retarding action of sugar is probably generated by the prevention of the formation of C-SH (Birchall and Thoma, 1984). However, the exact effects of sugar depend greatly on the chemical composition of cement (Neville, 1995).

The mechanism of the action of retarders has not been established with certainty (Neville, 1995). It is likely that they modify the crystal growth or morphology (Young et al., 1973), becoming adsorbed on the rapidly formed membrane of hydrated cement and slowing down the growth of calcium hydroxide nuclei (Banfill, 1986). These actions result in a more efficient barrier to further hydration than in the case without an admixture. Retarders do not alter the composition or identity of products of hydration (Seligmann and Greening, 1964).

2.3.2 Water-reducing Admixtures

According to ASTM C 494 – 10, admixtures which are only water-reducing are called Type A, but if the water-reducing properties are associated with retardation, then the admixtures are classified as Type D.

The two main groups of admixtures of Type D are: (a) lignosulfonic acids and their salts, and (b) hydroxylated carboxylic acids and their salts (Neville, 1995). The principal active components of the admixtures are surface-active agents. These are substances which are concentrated at the interface between two immiscible phases and which alter the physico-chemical forces acting at this interface. The substances are adsorbed on the cement particles, giving them a negative charge which leads to repulsion between the particles, that is to their deflocculation, and results in stabilizing their dispersion; air bubbles are also repelled and cannot attach themselves to the cement particles. Because flocculation traps some water, and also because where cement particles touch one another, their touching surfaces are not available for early hydration, water-reducing admixtures increase the surface area of cement which can undergo initial hydration and also increase the amount of water available for hydration. In addition, the electrostatic charge causes the development around each particle of a sheath of oriented water molecules which prevent a close approach of the particles to one another. The particles have, therefore, a greater mobility, and water freed from the restraining influence of the flocculated system becomes available to lubricate the mix so that the workability is increased (Prior and Adams, 1960).

2.3.3 Superplasticizers

The use of superplasticizers began in 1960s in Japan and Germany. It was a milestone in concrete technology and in the field of construction (Malhotra, 1997, Shah et al., 2014). Kenichi Hattori of Japan introduced the first superplasticizer in 1964 which contained beta-naphthalene sulfonates (Shah et al., 2014). The second superplasticizer, Melment contained sulphonated melamine formaldehyde condensate and was introduced in Germany in the same year (Jerath and Yamane, 1987). After a decade in 1970, the use of superplasticizers started in the American continent (Sidney, 2011).

The superplasticizers are poly-electrolytes of organic origin, which function like the dispersing chemical media in heterogeneous systems (Papayianni, 2005). The main difference between plasticizers and superplasticizers is in the extent rather than in the type of performance. The slump increase at a given mix composition is higher for the latter (Collepardi, 1998). Superplasticizers can be classified according to following polymer groups (Sidney, 2011):

(i) Sulphonated melamine-formaldehyde condensates (SMF)
(ii) Sulphonated naphthalene-formaldehyde condensates (SNF)
(iii) Modified lignosulphonates (MLS)
(iv) Polycarboxylate derivatives

The origins of these superplasticizers are described in **Table 2.2**.

Table 2.2. Origins of different types of superplasticizers (Rixom and Mailvaganam, 1999)

Type	Origin
Sulphonated melamine-formaldehyde	Manufactured by normal resinification of melamine – formaldehyde.
Sulphonated naphthalene-formaldehyde	Produced from naphthalene by oleum or SO_3 sulphonation; subsequent reaction with formaldehyde leads to polymerization and the sulfonic acid is neutralized with sodium hydroxide or lime.
Lignosulphonates	Derived from neutralization, precipitation, and fermentation processes of the waste liquor obtained during production of paper-making pulp from wood.
Polycarboxylic ether	Free radical mechanism using peroxide initiators is used for polymerization process in these systems.

2.4 Fresh Properties of Concrete

2.4.1 Effect of Types of Chemical Admixture

Retarders generally slow down the hardening of the paste although some salts may speed up the setting but inhibit the development of strength. Retarders are useful in concreting in hot weather, when the normal setting time is shortened by the higher temperature, and in preventing the formation of cold joints. In general, they prolong the time during which concrete can be transported, placed and compacted (Neville, 1995).

Young (1972) observed that, the effectiveness of a retarding admixture depends on the time when it is added to the mix: a delay of even 2 minutes after water has come into contact with the cement increases the retardation.

Investigation conducted by Whiting and Dziedzic (1992) suggests that, the bleeding rate and bleeding capacity of concrete increase with the addition of retarders.

Neville (1995) mentioned that, concrete containing a water-reducing admixture generally exhibits low segregation. Water-reducing admixtures improve the properties of fresh concrete made with poorly graded aggregate, e.g. a harsh mix.

Baskoca et al. (1998) observed that, combination of retarding and water reducing plasticizers imparts higher workability to concrete than water reducing plasticizer.

Meyer (1979) found in his study that, at a given water/cement ratio and water content in the mix, the dispersing action of superplasticizers increases the workability of concrete, typically by raising the slump from 75 mm to 200 mm. According to ACI 237R (2007), even a higher slump can be achieved in self-compacting concrete. The resulting concrete can be placed with little or no compaction and is not subject to excessive segregation.

Ghosh and Malhotra (1978) reported that superplasticized concrete with reduced W/C exhibits no or less bleeding compared to conventional concrete. However, Ramachandran et al. (1998) stated that, the rate of bleeding may increase if there are insufficient fines in the concrete.

2.4.2 Effect of Dosage of Chemical Admixture

Rixom and Mailvaganam (1999) reported that, an increased dosage of chemical admixture increases the workability. **Fig. 2.2** illustrates the effect.

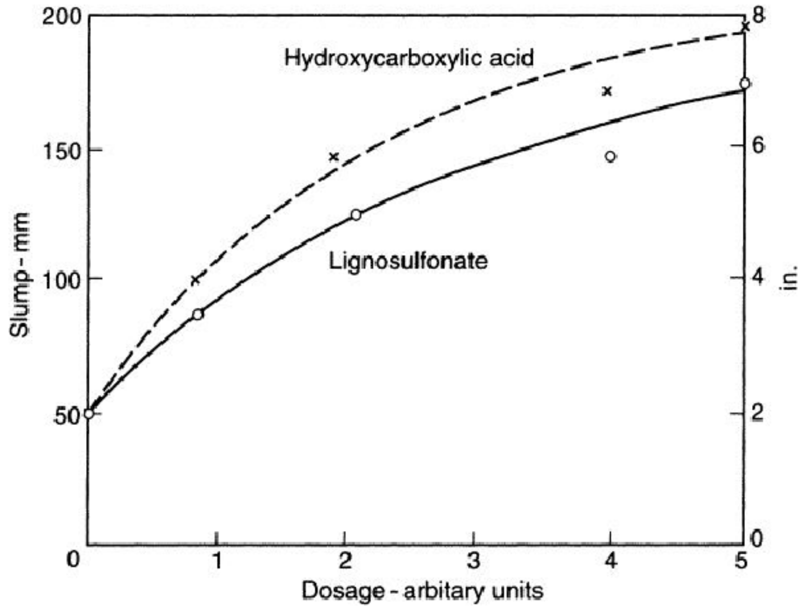

Fig. 2.2. Influence of dosage of chemical admixtures on slump (Rixom and Mailvaganam, 1999)

Several studies drew similar conclusion that, for a given W/C ratio the workability of concrete increases with the increase of the dosage of superplasticizer (Alsadey, 2012, Muhit, 2013, Rao and Kiran, 2015).

2.4.3 Effect of Repeated Dosages of Admixture

One way to deal with the issue of slump loss is to use repeated dosages of chemical admixtures. Dodson (1990) observed that large increase in slump of superplasticized concrete can be maintained for several hours by applying repeated dosages. He used naphthalene-based superplasticizer for retempering; water/cement ratio was 0.5; the initial dosage and each of the subsequent three redosages were the same, namely 0.4 percent of solids by mass of cement. Hattori (1979) and Malhotra (1980) also observed similar results in their studies. **Fig. 2.3** shows the effect of repeated dosages of naphthalene-based superplasticizer on slump of concrete.

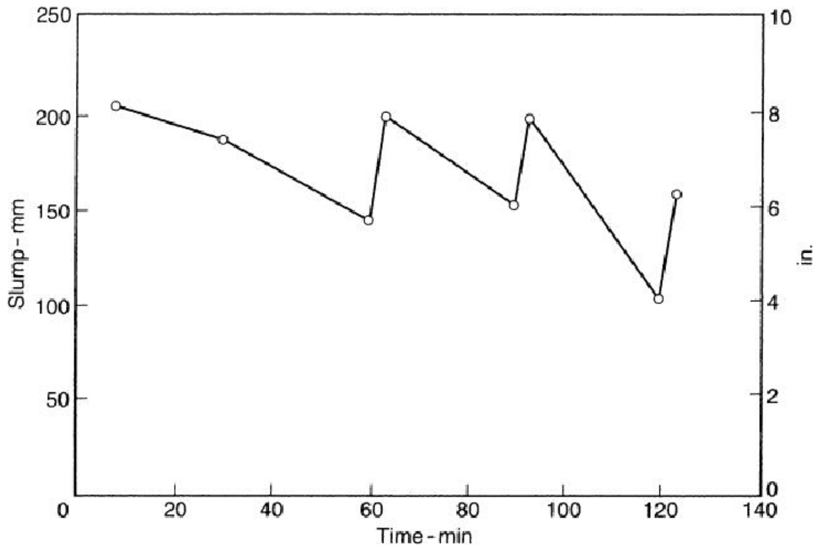

Fig. 2.3. Influence of re-dosage of naphthalene-based superplasticizer on slump of fresh concrete (Dodson, 1990)

2.4.4 Effect of Temperature

Sampebulu' (2012) found that, if the fresh concrete is prevented from evaporation, slump loss is caused solely by increased temperature of concrete. **Fig. 2.4** shows relation between slump and mixed concrete temperature depending upon the results of Sampebulu's (2012) study.

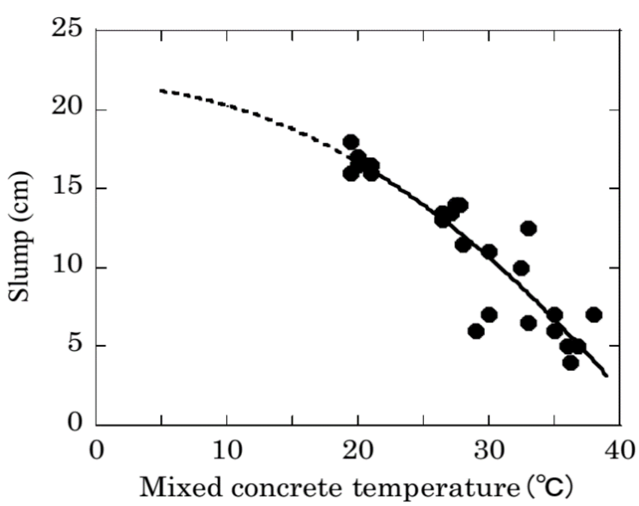

Fig. 2.4. Relation between slump and concrete temperature (Sampebulu', 2012)

Massaza and Testolin (1980) observed that, the retarding effect becomes smaller at higher temperatures and some retarders cease to be effective at extremely high ambient temperatures, about 60 °C.

Mehta and Monteiro (2006) stated that, under hot weather, a concrete mixture exhibiting an unusually large loss of slumps during the first 30 to 60 minutes may have the effect of making the mixing, placing, compacting, and finishing operations difficult or, at times, even impossible. Many researchers drew similar conclusion that, the workability of fresh concrete decreases significantly at high temperatures (Wang et al., 2014, Ghafoori and Diawara, 2010, Munday, 1976, Mailvaganam, 1979, Matsufuji et al. 1988, Soroka and Ravina, 1998, Burg, 1996).

Retempering fresh concrete with superplasticizers is an effective technique to prevent slump loss at high temperatures (Samarai et al., 1989). Present study targets to examine the fresh properties of concrete by both retempering the fresh concrete and controlling the mixing temperature.

2.4.5 Effect of Sand to Total Aggregate Volume Ratio

Su et al. (2002) examined the fresh and hardened properties of concrete for different s/a ratios. The results suggest that, the slump of fresh concrete increases with increasing s/a.

Jau et al. (2004) recorded slump results at 15 minutes intervals and found two different effects of s/a ratio on workability of superplasticized concrete for two different W/C ratios. They observed that, in case of W/C = 0.55, the slump values recorded at 15 minutes intervals were higher for s/a = 0.55 than those for s/a = 0.5. On the other hand, in case of W/C = 0.6, apart from the initial slump value all other slump values observed at 15 minutes intervals were higher for s/a = 0.5 in comparison to s/a = 0.55. The initial slump values for s/a = 0.5 and s/a = 0.55 were equal in case of W/C = 0.6.

Larrard (1987) found that, workability of concrete mix increases with the increase of s/a ratio up to s/a = 0.55, and after that, workability starts to decrease with the increase of s/a.

Li (2011) stated that, increasing s/a ratio increases the cohesiveness of concrete mix. Sizov (1997) stated that, an excessive amount of sand compared to the optimal causes a high consumption of cement, and its too low content leads to segregation and bleeding of concrete.

2.4.6 Effect of Cement Content

Yurdakul (2010) observed that, for a given W/C, workability decreases as cement content (thus paste content) decreases, because of having insufficient paste to lubricate the aggregates. Some researchers concluded that, for a given water content, decreasing the cement content increases stiffness of concrete with having poor workability (Lamond and Pielert, 2006, Mehta and Monteiro, 2006).

However, other studies suggest that concrete with high cement content shows high cohesiveness and becomes sticky (Lamond and Pielert, 2006, Mehta and Monteiro, 2006). Thus appropriate cement content should be used to achieve the desired workability.

2.5 Hardened Properties

2.5.1 Effect of Types of Chemical Admixture

2.5.1.1 Compressive Strength

Bloem (1959) observed, when sugar is used as a controlled set retarder, the early strength of concrete is severely reduced. But investigation conducted by Ashworth (1965) suggests that, beyond about 7 days, there is an increase in strength of several percent compared with a non-retarded mix.

Water-reducing admixtures reduce the water content of a mix, usually by 5 or 10 percent and sometimes in concretes of very high workability up to 12 percent. (Neville, 1995, Collepardi, 1998). Thereby, water-reducing admixtures contribute to dispersion of cement particles. Uniform distribution of the dispersed cement throughout the concrete eventually contribute to higher strength (Prior and Adams, 1960, Foster, 1960).

Hewlett and Rixom (1979) stated that, a superplasticizer is capable of reducing water requirements at a given slump by about 25-35%, whereas a plasticizer can reduce water contents by only about 5-12%. **Fig. 2.5**, illustrates that, using melamine-based superplasticizer, up to 30% of water reduction can be obtained (Aignesberger and Kern, 1981).

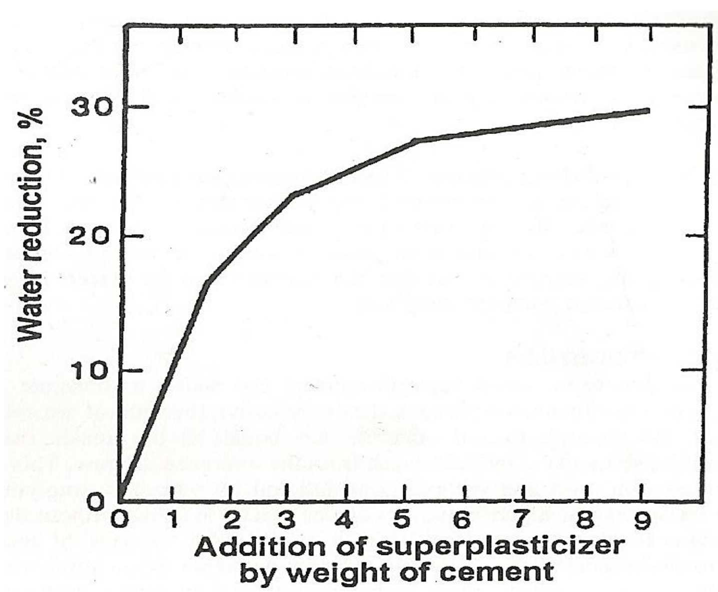

Fig. 2.5. Water reduction obtained due to the addition of superplasticizer

(Aignesberger and Kern, 1981)

Thus the production of high strength concrete can be achieved, because superplasticizers exhibit high workability at a very low W/C ratio (Papayianni et al., 2005, Yamakawa et al., 1990, Aignesberger and Kern, 1981). High Performance

Concrete (HPC) produced using superplasticizers can achieve 100 – 150 MPa of 28-day cylindrical strength reducing the water/cement ratio down to 0.2 (Rixom and Maivaganam, 1999, Neville, 1995).

It is evident from previous studies that superplasticizers reduce the water demand of the fresh concrete mix thereby increase the strength of hardened concrete. But literature gives contradictory results regarding the strength behavior of superplasticized concrete in comparison to conventional concrete when the W/C ratio is kept similar to that of conventional concrete. Some of the researchers concluded that, if W/C is not changed, adding superplasticizer to the concrete mix increases the compressive strength of hardened concrete (Mohammed and Hamada, 2003, Rao and Kiran, 2015, Alsadey, 2012). On the other hand, some studies suggest, due to addition of superplasticizer the compressive strength decreases (Al-Kadhimi et al., 1987, Jerath and Yamane, 1987). In this study, a comparative analysis has been conducted between the compressive strength behaviors of superplasticized concrete and conventional concrete for constant W/C.

2.5.1.2 Tensile Strength

Shah et al. (2014) found that, for a constant W/C ratio, the tensile strength of superplasticized concrete is higher in comparison to conventional concrete.

On the other hand, Jerath and Yamane (1987) concluded that, the tensile strength of superplasticized concrete is smaller than that of conventional concrete. Current study analyses the tensile strength behavior of different chemical admixtures to address the controversy.

2.5.1.3 Ultrasonic Pulse Velocity (UPV)

To assess the behavior of concrete structures using non-destructive techniques has 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 in the same way as the audible sound waves. Since ultrasonic waves do not travel through air or vacuum, couplant (a gel like substance) is needed to fill the voids between transducers and concrete surface in order to transmit or receive the waves (Galan, 1990).

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 behavior. 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).

Tharmaratnam and Tan (1990) provided the empirical formula of the combined UPV and ultrasonic pulse amplitude (UPA). Liang and Wu (2002) studied theoretical elucidation of the empirical formulae for the UPV and UPA and combined methods. Ye et al. (2004) determined the development of the microstructure in cement-based materials by means of numerical simulation and UPV.

Over decades, many studies were performed to identify the relation between concrete strength and UPV (Facaoaru, 1969, Yang et al., 2010, Ben-Zeitun, 1986, Ravindrarajah, 1997, Price, 1996, Tang et al., 2007).

Some studies were conducted to figure out the relationship between compressive strength and UPV of superplasticized concrete. Mardani-Aghabaglou et al. (2013) proposed a linear relationship between compressive strength and UPV of superplasticized self-consolidating concrete. On the other hand, Demirboğa et al. (2004), Tang et al. (2007), Ravindrarajah et al. (1988) and Trtnik et al. (2009) proposed exponential relationships.

In this study, UPVs have been measured for concrete cylinders prepared with different chemical admixtures. A relationship between compressive strength and UPV of superplasticized concrete has been proposed.

2.5.1.4 Durability Aspects

Mohammed and Hamada (2003) conducted a detailed investigation on concrete specimens made with different types of chemical admixtures after 10 years of tidal exposure. They observed, use of water reducing admixtures or superplasticizers prevent chloride ingress in concrete exposed to marine environment for long period of time. Amongst different types of admixture naphthalene group of admixtures showed best performance in reducing chloride ingress. However, polycarboxyl group of chemical admixtures resulted more chloride ingress compared to other admixtures.

Mohammed and Hamada (2003) also observed that, after 10 years concrete specimens prepared with naphthalene group of chemical admixtures imparted higher compressive strength as well as higher Young’s modulus compared to other types of admixture.

Mukherjee and Chojnacki (1979) found superplasticized concrete to impart satisfactory resistance to salt scaling.

Previous studies indicate that, the resistance to sulphate attack of superplasticized concrete is no different than that of conventional concrete (Brooks et al., 1979, Collepardi and Corradi, 1979).

2.5.1.5 Miscellaneous Properties

Although superplasticizers do not react by a chemical action on hydrated products, they affect the microstructure of cement gel and concrete, for example in superplasticized concrete the porosity, bleeding and segregation decrease significantly (Ghosh and Malhotra, 1978, Song et al., 2001).

Some researchers reported that concrete prepared with several superplasticizers imparts larger shrinkage than traditional concrete (Ghosh and Malhotra, 1978, Jasiczak and Szymański, 2004). However, there are other superplasticizers which contain shrinkage reducing agent (SRA) (Sugiyama et al., 2000).

Literature suggests that some superplasticizers (specially lignosulfonic superplasticizers) in high dosages result delaying the curing of concrete (Papayianni et al., 2005). But the superplasticizers of high reactivity (such as polycarboxylic products), which in high dosages do not have the side-effect of delaying the curing of concrete, have made the production of concrete with a big volume of fly ash or slag possible (Langley et al., 1989).

2.5.2 Effect of Dosage of Chemical Admixture

Previous studies gave quite contradictory data on the effect of dosage of chemical admixtures on compressive strength of concrete. Jerath and Yamane (1987) found that, for a given W/C both compressive strength, tensile strength, young's modulus of concrete decrease with the increase of chemical admixture dosage. On the contrary, Rao and Kiran (2015) observed that compressive strength and tensile strength of concrete increase with the increase of chemical admixture dosage.

Where, Devi and John (2014) observed no significant effect of the dosage of chemical admixture on the compressive strength of concrete.

Some of the studies suggest that, the compressive strength of concrete initially increases with the increase of superplasticizer dosage but after a certain amount of dosage the strength of concrete starts to decrease (Alsadey, 2012, Muhit, 2013, Shah et al., 2014).

Shah et al. (2014) observed similar effect on the tensile strength of superplasticized concrete i.e. the tensile strength of concrete becomes maximum for an optimum dosage of superplasticizer.

Therefore, this study aims to improve the understanding of the effect of admixture dosage on the fresh and hardened properties of concrete. The investigation was done taking different types of chemical admixtures into consideration.

2.5.3 Effect of Repeated Dosages of Chemical Admixture

There is much controversy in the literature regarding the effect of retempering fresh concrete with chemical admixtures on the compressive strength of concrete. Al-Kadhimi et al. (1987) analyzed the behavior of different chemical admixtures and observed that, for almost all the admixtures, retempered concrete exhibited lower compressive strength than conventional concrete.

On the contrary, Erdoğdu (2005) observed that concrete with no retempering revealed higher compressive strength in comparison to the concrete retempered with water; concrete retempered with superplasticizer imparted even higher strength. However, results obtained from the study indicate that, for successive retempering, strength would become maximum after certain time; and then the strength would gradually decrease with time. Kırca et al. (2002) conducted experimental investigation for different dosages of superplasticizers, and in most of the cases, compressive strength exhibited by retempered concrete was higher than the strength exhibited by concrete without retempering.

2.5.4 Effect of Temperature

Wang et al. (2014) found in their study that the early age compressive strength of concrete increased with the increase of temperature. Higher temperature promotes the early hydration of cement and accelerates the setting and hardening of cement and concrete; eventually increases the early compressive strength.

Burg (1996) observed that, the effect of high temperature on compressive strength of concrete was reversed after 7 days. Price (1951) found similar results in his investigation. **Fig. 2.6** shows after 7 days the compressive strength of concrete decreased with the increase in temperature.

It can also be seen from **Fig. 2.6** that, the concrete cast and cured at 10 °C exhibited higher 28-day compressive strength than the concrete cast at 23 °C but cured at 10 °C. This indicates that, despite controlling the temperature at later stage of curing, the compressive strength of concrete may reduce if the temperature of fresh concrete is high during casting.

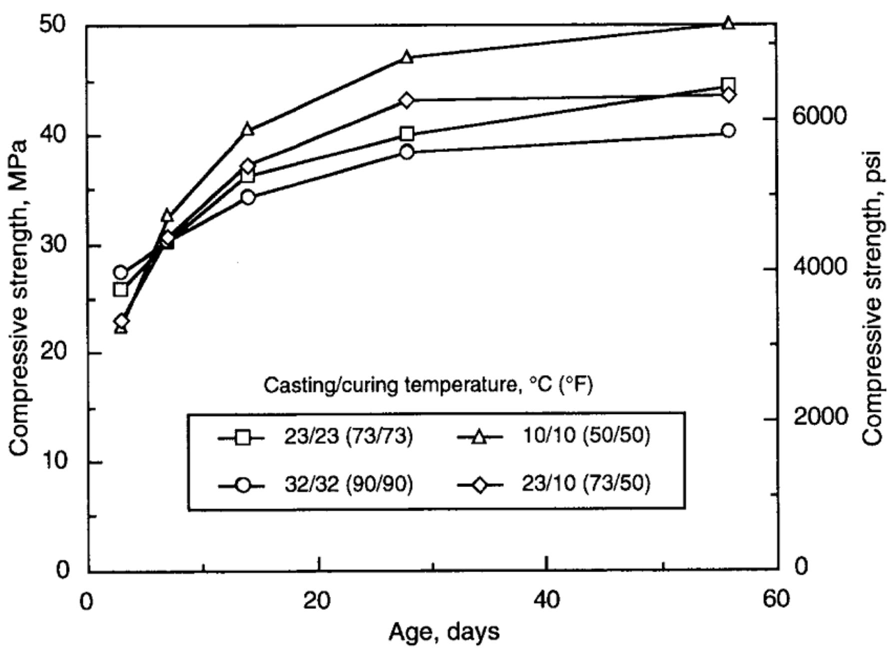

Fig. 2.6. Influence of temperature on compressive strength of concrete (Burg, 1996)

The explanation of the adverse effects of a high early temperature on later strength has been extended by Verbeck and Helmuth (1968), who stated that the rapid initial rate of hydration at higher temperatures retards the subsequent hydration and produces a non-uniform distribution of the products of hydration within the paste. The reason for this is that, at the high initial rate of hydration, there is insufficient time available for the diffusion of the products of hydration away from the cement particle and for a uniform precipitation in the interstitial space (as is the case at lower temperatures). As a result, a high concentration of the products of hydration is built up in the vicinity of the hydrating particles, and this retards the subsequent hydration and adversely affects the long-term strength.

In present study, the temperature of the fresh superplasticized concrete has been reduced during the mixing process and the behavior of the hardened concrete has been examined.

2.5.5 Effect of Sand to Total Aggregate Volume Ratio

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.

Jau et al. (2004) obtained similar results in their study. They observed that the compressive strength exhibited by cylinders with s/a = 0.55 is higher in comparison to the cylinders with s/a = 0.50 for both W/C = 0.50 and W/C = 0.60.

Again, Su et al. (2002), Yang and Huang (1998) concluded that the Young’s modulus of concrete is not significantly affected by the change in s/a ratio.

2.5.6 Effect of 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. Literature suggests that, with the increase of cement content up to a certain limit, the strength of concrete increases. However, high cement content in a mixture does not contribute to greater strength than the required design strength (Wasserman et al., 2009 and Popovics, 1990). On the contrary, high cement content causes the concrete to become sticky as well as have shrinkage and cracking problems. Shrinkage of concrete may thereby result in subsequent decrease in the strength of concrete (Neville, 2011). Therefore, cement content should be balanced to achieve maximum performance while minimizing risk of these problems.

Some researchers came to conclusion that strength of concrete is 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 and 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, some researchers observed that, achieving high strength by increasing the cement content is difficult when cement content is below 350 kg/m^3 (Rixom and Mailvaganam, 1999). Therefore, these findings show a direct relationship between strength and cement content as opposed to the Abrams rule.

CHAPTER 3: EXPERIMENTAL PROGRAM

3.1 General

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

3.2 Preparation of Materials

Prior to the preparation of mixtures, both coarse and fine aggregates were brought to saturated surface dry (SSD) condition so that the W/C ratio of the mix would remain unaffected.

3.2.1 Coarse Aggregate

Crushed stones were collected from local market. The maximum size of aggregates was 19 mm. Prior to casting, these coarse aggregates were sieved separately to satisfy ASTM C 33 – 03. Before the preparation of concrete mixtures, the aggregates were kept in submerged condition for 24 hours and were rubbed with clean cloth to eliminate excess water from the aggregate surface and to ensure SSD condition of the aggregates.

3.2.2 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 containers to avoid moisture loss.

3.2.3 Water

During the preparation of Type 6 concrete, ice cubes were used along with liquid water to keep the temperature of the concrete mix low.

3.3 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 3.1**.

Table 3.1. Specifications followed to test material properties

Name of the Property Evaluated	Specification 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

3.3.1 Coarse Aggregate

The gradation of coarse aggregates was controlled as per ASTM C 33 – 03. The gradation followed in this study is shown in **Table 3.2**, and the gradation curve is shown in **Fig. 3.1**. 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 3.3**.

3.3.2 Fine Aggregate

For this study, locally available Sylhet sand was used as fine aggregate. 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 3.4**. 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 **Fig. 3.2**.

3.3.3 Cement

CEM Type II B–M cement was used as binding material in this study, which conforms to BDS EN 197 – 1: 2000, and ASTM C 595. 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. The composition of the mineral components is given in **Table 3.5** (as specified by the manufacturer).

3.3.4 Chemical Admixture

Chemical admixtures used in present study satisfy the requirements of ASTM C 494 – 98. Among the chemical admixtures, WR is a water reducer, and the rest of the admixtures are superplasticizers. The ASTM Type and chemical property of each chemical admixture are mentioned in **Table 3.6**.

3.3.5 Water

Water used in this study for concrete mixing and curing was potable tap water, unit weight of the water was 1000 kg/m^3. During the mixing process of Type 6 concrete, ice cubes were used along with liquid water. The temperature of water mixed with ice cubes was 0 ± 2 °C.

Table 3.2. Gradation of coarse aggregate (according to ASTM C 33)

Nominal Size	Amounts Finer than Each Laboratory Sieve, Mass Percent					
	25.0 mm	19.0 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm
19.0 to 9.5 mm	100	95	37.5	7.5	2.5	-

Table 3.3. Properties of coarse aggregate

Aggregate Type	Specific Gravity	Absorption Capacity (%)	Abrasion (%)	SSD Unit Weight (kg/m^3)	Fineness Modulus
Crushed Stone	2.56	2.39	38.3	1549	6.95

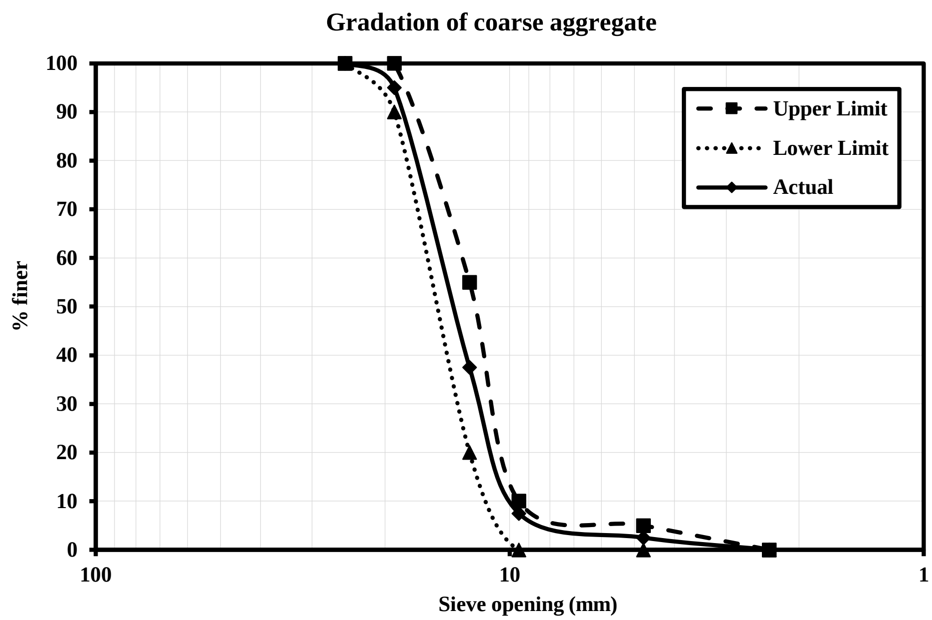

Fig. 3.1. Gradation of coarse aggregate

Table 3.4. Properties of fine aggregate

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

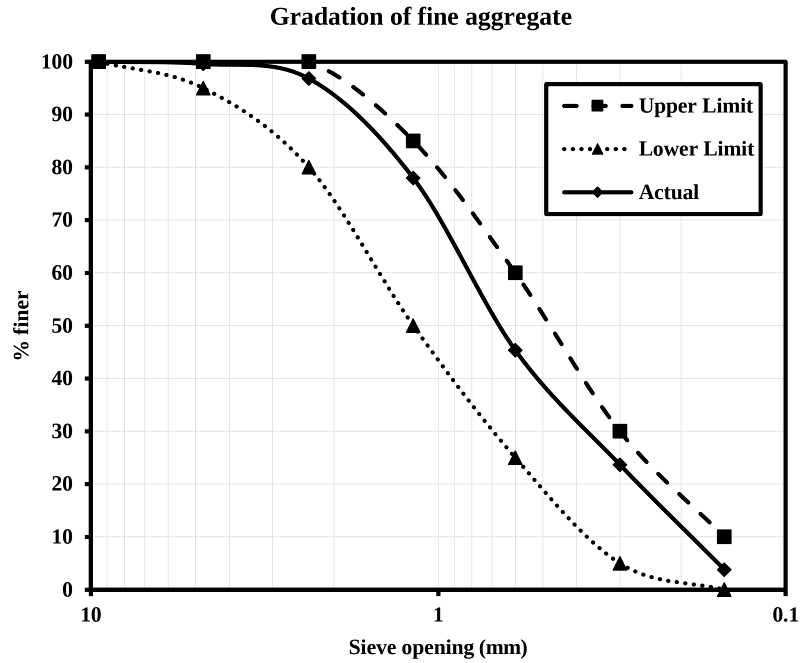

Fig. 3.2. Gradation of fine aggregate

Table 3.5. Composition of cement as per manufacturer

Component	Percentage
Clinker	65-79%
Slag, Fly Ash, and Limestone	21-35%
Gypsum	0–5%

Table 3.6. ASTM C 494 types and chemical properties of admixtures

Chemical Admixture	ASTM C 494 Type	Chemical Property
WR	A and D: Water-reducing and retarding	Lignosulphonate based
SP1	A and F: High range water reducing or superplasticising	Naphthalene sulphonate based
SP2	F: High range water reducing or superplasticising	Organic polymers
SP3	F: High range water reducing or superplasticising	Second generation polycarboxylic ether based
SP4	G: High range water reducing and retarding, or superplasticising	Modified polycarboxylic ether based
SP5	B, D and G: High range water reducing and retarding, or superplasticising	Modified polycarboxylic ether based
SP6	G: High range water reducing and retarding, or superplasticising	Sulphonated naphthalene polymer based
SP7	B, D and G: High range water reducing and retarding, or superplasticising	Naphthalene sulphonate based
SP8	A and F: High range water reducing or superplasticising	Synthetic polymers

3.4 Concrete Mixture Proportion

Six different types of concrete mixtures namely Types 1, 2, 3, 4, 5 and 6 were prepared with different types of chemical admixtures. A reference concrete mix without chemical admixture was also prepared. Each Type 1 concrete mixture was prepared using the average of the maximum and minimum dosages of every chemical admixture recommended by respective manufacturer. On the other hand, rest of the 5 mixture types were prepared using the maximum recommended dosages of admixtures. In Types 1, 2 and 3 mixtures, W/C ratio, s/a ratio and cement content were 0.4, 0.4 and 340 kg/m^3. In Type 4 mixtures the s/a ratio was increased to 0.45, where the rest of the properties of Type 4 mixtures were similar to Type 3 mixtures. During the preparation of Type 5 and Type 6 mixtures the cement content was raised to 380 kg/m^3 of concrete but the W/C ratio and s/a ratio were kept similar to Type 4 mixtures. In the reference mix W/C, s/a and cement content were respectively 0.4, 0.4 and 340 kg/m^3. 100 mm by 200 mm cylindrical concrete specimens were made with the concrete mixtures for assessing the hardened properties of superplasticized concrete. The W/C ratio, s/a ratio, cement content and admixture dosage type of each mixture are summarized below:

Type 1: W/C = 0.4; s/a = 0.4; cc = 340 kg/m^3; average admixture dosage.

Type 2: W/C = 0.4; s/a = 0.4; cc = 340 kg/m^3; maximum admixture dosage.

Type 3: W/C = 0.4; s/a = 0.4; cc = 340 kg/m^3; maximum admixture dosage in two stages – 2/3 at the beginning, 1/3 when slump ≤ 3 cm.

Type 4: W/C = 0.4; s/a = 0.45; cc = 340 kg/m^3; maximum admixture dosage in two stages – 2/3 at the beginning, 1/3 when slump ≤ 3 cm.

Type 5: W/C = 0.4; s/a = 0.45; cc = 380 kg/m^3; maximum admixture dosage in two stages – 2/3 at the beginning, 1/3 when slump ≤ 3 cm.

Type 6: W/C = 0.4; s/a = 0.45; cc = 380 kg/m^3; maximum admixture dosage in two stages – 2/3 at the beginning, 1/3 when slump ≤ 3 cm; fresh concrete temperature reduced.

Reference mix: W/C=0.4; s/a=0.4; cc=340 kg/m^3; no admixture.

A total of 27 independent cases and 297 cylindrical specimens were investigated. The mixture proportions of all 27 cases are summarized in **Table 3.7**. The notations used for the cases are explained at the bottom of **Table 3.7**. Materials required to prepare concrete mixtures are mentioned in **Table 3.8**. The dosage limits of admixtures recommended by their manufacturers are presented in **Table 3.9**.

Table 3.7. Mixture proportion of concrete

Concrete Type	s/a	W/C	Case ID	Unit Content (kg/m^3)				Admixture Name (Dosage, ml/100kg of Cement)
				Cement	Sand	Aggregate	Water	
Type 1	0.40	0.40	T1WRSA40WC40C340	340	743	1115	136	WR (300)
			T1SP1SA40WC40C340	340	743	1114	136	SP1 (550)
			T1SP2SA40WC40C340	340	741	1112	136	SP2 (870)
			T1SP3SA40WC40C340	340	743	1114	136	SP3 (500)
			T1SP4SA40WC40C340	340	742	1113	136	SP4 (650)
			T1SP5SA40WC40C340	340	742	1113	136	SP5 (700)
			T1SP6SA40WC40C340	340	740	1109	136	SP6 (1400)
			T1SP7SA40WC40C340	340	741	1112	136	SP7 (950)
			T1SP8SA40WC40C340	340	740	1110	136	SP8 (1200)
Type 2	0.40	0.40	T2WRSA40WC40C340	340	743	1114	136	WR (400)
			T2SP1SA40WC40C340	340	738	1106	136	SP1 (2000)
			T2SP2SA40WC40C340	340	741	1111	136	SP2 (1140)
			T2SP3SA40WC40C340	340	740	1110	136	SP3 (1200)
			T2SP4SA40WC40C340	340	740	1110	136	SP4 (1200)
			T2SP5SA40WC40C340	340	740	1110	136	SP5 (1200)
			T2SP6SA40WC40C340	340	738	1107	136	SP6 (1800)
			T2SP7SA40WC40C340	340	740	1110	136	SP7 (1200)
			T2SP8SA40WC40C340	340	739	1109	136	SP8 (1500)
Type 3	0.40	0.40	T3WRSA40WC40C340	340	743	1114	136	WR (400)
			T3SP3SA40WC40C340	340	740	1110	136	SP3 (1200)
			T3SP4SA40WC40C340	340	740	1110	136	SP4 (1200)
			T3SP5SA40WC40C340	340	740	1110	136	SP5 (1200)
			T3SP6SA40WC40C340	340	738	1107	136	SP6 (1800)
Type 4	0.45	0.40	T4SP6SA45WC40C340	340	831	1015	136	SP6 (1800)
Type 5	0.45	0.40	T5SP6SA45WC40C380	380	797	974	152	SP6 (1800)
Type 6	0.45	0.40	T6SP6SA45WC40C380	380	797	974	152	SP6 (1800)
Reference mix (without admixture)	0.40	0.40	RMSA40WC40C340	340	744	1117	136	-
Total number of cases = 27								
Cylinders per case = 3 × 3 (compressive strengths at 7 days, 28 days and 90 days) + 2 (splitting tensile strengths at 28 days) = 11								
Total number of cylinders = 11 × 27 = 297								
T1WRSA40WC40C340; here T1 represents Type 1 concrete, WR represents chemical admixture WR, SA40 represents s/a ratio of 0.40, WC40 represents W/C ratio of 0.40, C340 represents cement content of 340 kg/m^3. RMSA40WC40C340; here RM represents reference mix, SA40 represents s/a ratio of 0.40, WC40 represents W/C ratio of 0.40, C340 represents cement content of 340 kg/m^3.								

Table 3.8. Materials required to prepare concrete mixtures

Concrete Type	s/a	W/C	Case ID	Materials Required Per Case (g)				
				Cement	Sand	Aggregate	Water	Admixture
Type 1	0.40	0.40	T1WRSA40WC40C340	5875	12843	19264	2350	22
			T1SP1SA40WC40C340	5875	12829	19243	2350	40
			T1SP2SA40WC40C340	5875	12810	19214	2350	64
			T1SP3SA40WC40C340	5875	12831	19247	2350	37
			T1SP4SA40WC40C340	5875	12823	19235	2350	48
			T1SP5SA40WC40C340	5875	12819	19230	2350	51
			T1SP6SA40WC40C340	5875	12779	19167	2350	103
			T1SP7SA40WC40C340	5875	12805	19207	2350	70
			T1SP8SA40WC40C340	5875	12790	19186	2350	88
Type 2	0.40	0.40	T2WRSA40WC40C340	5875	12836	19255	2350	29
			T2SP1SA40WC40C340	5875	12743	19115	2350	147
			T2SP2SA40WC40C340	5875	12795	19192	2350	84
			T2SP3SA40WC40C340	5875	12790	19186	2350	88
			T2SP4SA40WC40C340	5875	12790	19186	2350	88
			T2SP5SA40WC40C340	5875	12790	19186	2350	88
			T2SP6SA40WC40C340	5875	12755	19133	2350	132
			T2SP7SA40WC40C340	5875	12790	19186	2350	88
			T2SP8SA40WC40C340	5875	12772	19159	2350	110
Type 3	0.40	0.40	T3WRSA40WC40C340	5875	12836	19255	2350	29
			T3SP3SA40WC40C340	5875	12790	19186	2350	88
			T3SP4SA40WC40C340	5875	12790	19186	2350	88
			T3SP5SA40WC40C340	5875	12790	19186	2350	88
			T3SP6SA40WC40C340	5875	12755	19133	2350	132
Type 4	0.45	0.40	T4SP6SA45WC40C340	5875	14350	17538	2350	132
Type 5	0.45	0.40	T5SP6SA45WC40C380	6566	13775	16835	2626	148
Type 6	0.45	0.40	T6SP6SA45WC40C380	6566	13775	16835	2626	148
Reference mix (without admixture)	0.40	0.40	RMSA40WC40C340	5875	12861	19292	2350	-

T1WRSA40WC40C340; here T1 represents Type 1 concrete, WR represents chemical admixture WR, SA40 represents s/a ratio of 0.40, WC40 represents W/C ratio of 0.40, C340 represents cement content of 340 kg/m^3.

RMSA40WC40C340; here RM represents reference mix, SA40 represents s/a ratio of 0.40, WC40 represents W/C ratio of 0.40, C340 represents cement content of 340 kg/m^3.

Table 3.9. Recommended dosage limits of chemical admixtures

Admixture	Recommended Dosage Limit (ml/100 kg of cement)
SP1	500 – 2000
SP2	600 – 1140
SP3	500 – 1200
SP4	400 – 1200
SP5	400 – 1200
SP6	600 – 1800
SP7	400 – 1200
SP8	500 – 1500
WR	200 – 400

The mix proportion used in this study was done in weight basis. The unit contents of the ingredients present in 1 m^3 of concrete were calculated using the following equation:

$$\frac{C}{G_c\gamma_w} + \frac{S}{G_s\gamma_w} + \frac{A}{G_A\gamma_w} + \frac{V_{ad}C}{10^8} + \frac{Air\ (\%)}{100} = 1 \qquad (3.1)$$

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

V_{ad} = Volume of chemical admixture per 100 kg of cement (ml/100 kg of cement)

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

3.5 Experimental Setup

The concrete mixtures were subjected to prolonged mixing. Slump tests were performed at 15 minutes intervals until the final slump value became less than or equal to 2 cm. After recording the final slump value, concrete samples were prepared for casting.

After casting of concrete specimens, they were cured initially for 24 hours by covering the cylindrical molds with wet burlap to prevent moisture loss. The specimens were demolded after 24 hours of casting, followed by curing under water till the age of testing.

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 – 03.

3.6 Sample Preparation

3.6.1 Mold Preparation

Cylindrical molds of diameter 100 mm and height 200 mm were used for all concrete mixtures mentioned in **Table 3.7**. 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 – 03.

3.6.2 Mixing of Fresh Concrete

In each case, fresh concrete was subjected to prolonged mixing. A mixing machine was used for the mixing process. Trial mix was done for every case before the final mix. The procedure of mixing of fresh concrete is described below:

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

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: After that the mixing machine was switched on. The sand and cement was mixed for 30 seconds.

Step 6: Water and chemical admixture were 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 aggregates were then introduced inside the mixing machine and the mixing was continued for further 3 minutes. After 3 minutes, the mixing machine was stopped.

Step 8: A sample of the concrete mix was taken out of the mixing machine to determine the slump value. The procedure of slump test is described in section **3.6.3**. In every case slump test was performed within 5 minutes.

Step 9: The sample was again poured inside the mixing machine, and the machine was then turned on.

Step 10: After rotating for 10 minutes the machine was stopped, and *Step 8* and *Step 9* were repeated.

Steps 8, 9 and *10* were repeated continuously until the final slump value became less than or equal to 2 cm.

During the preparation of Types 3, 4, 5 and 6 mixtures, the dosage of admixture was applied in two stages, instead of applying the entire dosage with water at the beginning (as described in *Step 6*). At first, 2/3 of the dosage of admixture was applied with water, and the rest 1/3 was applied when the slump value became less than or equal to 3 cm.

In case of Type 6 mixture, instead of using plain water, ice was used partially to keep the temperature of the concrete mix low.

During the mixing process of Type 6 mixture, whenever the mixing machine was stopped, it was covered with a burlap chilled in ice melted water to keep the temperature of concrete mix low inside the mixing machine.

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 – 03.

A sample of freshly mixed concrete was placed and compacted by a tamping rod, in a mold shaped as the frustum of a cone. The tamping rod was a round, straight steel rod, 16 mm 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.

During the preparation of Type 6 concrete mixture, the slump cone and tamping rod were submerged continuously in ice melted water. After every 10 minutes, at the time of measuring each slump, the cone and the tamping rod were taken out of the ice melted water, and after recording the slump reading the cone and the rod were again submerged in the water.

3.6.4 Casting of Concrete Samples

In this study, concrete cylindrical specimens of diameter 100 mm and length 200 mm were made. The cylindrical samples were made according to ASTM C 31 – 03.

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. Tamping rod of diameter 10 mm and length 300 mm was used to compact the concrete poured in cylinders in two layers. 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 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 might 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 – 03. To prevent the evaporation of water from the unhardened concrete, each specimen was immediately covered with a 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 $^{\circ}$C from the time of demolding until the moment of testing. Each specimen was placed in a curing bath so as to allow free water on entire surface area of the specimen.

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 compressive strength, tensile strength, Young's modulus etc. In non-destructive tests (NDT), the specimen strength is determined without damaging the specimen. In this study also, concrete properties were evaluated by means of an NDT named ultrasonic pulse velocity (UPV) test.

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 – 03. In this method, compressive axial load was applied to concrete 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 then the cross-sectional area was calculated. To determine the compressive strength of a particular batch of concrete on a particular age, the average compressive strength of three specimens having diameter 100 mm and height 200 mm was taken as per guideline of ASTM C 39 – 03. 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 factor as specified by ASTM C 39 – 03.

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 – 03.

3.7.1.2 Splitting Tensile Strength

The splitting tensile strength of concrete was determined according to ASTM C 496 – 03, by applying a diametral compressive force along the length of cylindrical concrete specimens, until failure occurred. 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 (3.2).

$$T = \frac{2P}{\pi l d} \tag{3.2}$$

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 and length of each specimen were determined. Diameter was determined by averaging two readings.

3.7.1.3 Young's Modulus

The Young's modulus of each specimen was measured according to ASTM C 469 – 03, during compressive strength test of the specimen. A strain-measuring setup was attached with the specimen and then the specimen was placed 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 of 241 ± 34 kPa/s. Without interruption, the applied load and corresponding longitudinal strain were measured until the time of 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:

$$\text{Young's Modulus} = f_{0.0005}/0.0005 \tag{3.3}$$

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 (UPV)

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 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 stable transit time was displayed. The transit time was recorded for further calculation using the flowing equation:

$$UPV = L/T \tag{3.4}$$

Where, *UPV* is the ultrasonic 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.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 General

In this chapter, the results obtained throughout the investigation are summarized and discussed. The effects of types and dosages of chemical admixture on fresh properties (e.g. workability) and hardened properties (e.g. compressive strength, splitting tensile strength, Young's modulus and UPV) are described. The effects of temperature at the time of mixing, cement content and sand to total aggregate volume ratio on fresh and hardened properties of superplasticized concrete are also discussed. Different relationships are proposed for superplasticized concrete; namely relationships between compressive strength and Young's modulus, compressive strength and tensile strength, UPV and compressive strength.

4.2 Fresh Properties of Concrete

To analyze the fresh properties of concrete made with chemical admixture, six different types (namely Types 1, 2, 3, 4, 5 and 6) of concrete mixtures were prepared. The concrete mixtures were subjected to prolonged mixing and slump results were recorded at 15 minutes intervals. According to the JSCE guideline for concrete – 2007, for normal strength ready mix concrete, the minimum slump requirement at the place of unloading is 8 cm. Therefore, in this study the workability performance of each concrete mix was judged based on the time up to which the slump values were greater than 8 cm. The more was the time the better was the workability performance.

4.2.1 Effect of Types of Chemical Admixture

Fig. 4.2 and **Fig 4.3** show slump test results of Type 2 and Type 3 concrete mixtures respectively. During the preparation of Type 2 concrete mixtures, the maximum recommended dosages of admixtures were used. While in case of Type 3 mixtures the maximum dosage was applied in two stages. At first 2/3 of the admixture was applied at the beginning of mixing. After that, when the slump value became less than or equal to 3 cm, the rest 1/3 was applied. From both **Fig 4.1** and **Fig 4.2**, it can be seen that the sulphonated naphthalene polymer based superplasticizer SP6 showed best performances for both Type 2 and Type 3 mixtures. Type 2 and Type 3 mixtures with SP6 remained workable for longer period compared to other admixtures. The second best results were found for second generation polycarboxylic ether based superplasticizer SP3 for both Type 2 and Type 3 mixtures. The results also confirm that the workability performances of most of the superplasticizers were better in comparison to the performance of lignosulphonate based water reducer WR.

4.2.2 Effect of Increased Dosage of Chemical Admixture

Fig. 4.1 shows slump test results of Type 1 concrete mixtures. Each Type 1 concrete mixture was produced using the average of the maximum and minimum recommended dosages of chemical admixture. The entire dosage of admixture was applied at the beginning of mixing. Results shown in **Fig. 4.1** and **Fig 4.2** confirm that, for most of the admixtures Type 2 mixtures remained workable for longer periods compared to Type 1 mixtures. The initial slump values of mixtures prepared with WR and SP2 increased with the increase of their dosages but the final slump values at the end of 30 minutes didn’t change much. In case of SP4, SP7 and SP8 the initial slump values were greater for Type 2 mixtures than for Type 1 mixtures. Where, in case of SP1, SP3, SP5 and SP6 the initial slump values of Type 2 mixtures were smaller in comparison to those of Type 1 mixtures; but after 30 – 45 minutes the slump values of Type 2 mixtures increased and the values became greater than those of Type 1 mixtures except for SP3. However, in case of Type 2 concrete with SP3, slump became 8 cm at the end of 118.6 minutes; where in case of Type 1 concrete with SP3, slump became 8 cm at the end of 108.6 minutes.

4.2.3 Effect of Two-Stage Dosage of Chemical Admixture

It can be seen from **Fig. 4.3** that, for the preparation of Type 3 mixtures, when the last 1/3 of the dosage was applied, slump values again increased for all the admixtures. Slumps attained after the application of second dosage were very close to the initial slumps. Comparing the results shown in **Fig. 4.1**, **Fig. 4.2** and **Fig. 4.3** it can be understood that, except the Type 3 mixture prepared with SP5, all other Type 3 mixtures gave better results in comparison to Type 1 and Type 2 mixtures. In general, it can be said that, applying the dosage of admixture in two stages improved the workability performance of fresh concrete. The results of Type 1, Type 2 and Type 3 mixtures made with best three chemical admixtures are presented in **Fig. 4.4**. **Fig. 4.5** shows the workability performances of Type 1, Type 2 and Type 3 mixtures made with SP6 and SP3.

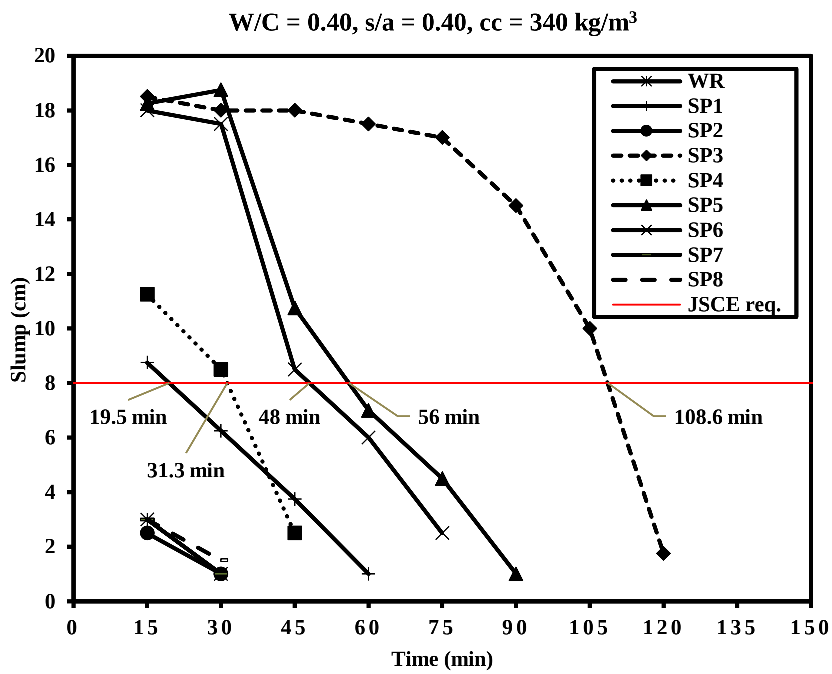

Fig. 4.1. Slump test results of Type 1 concrete mixtures

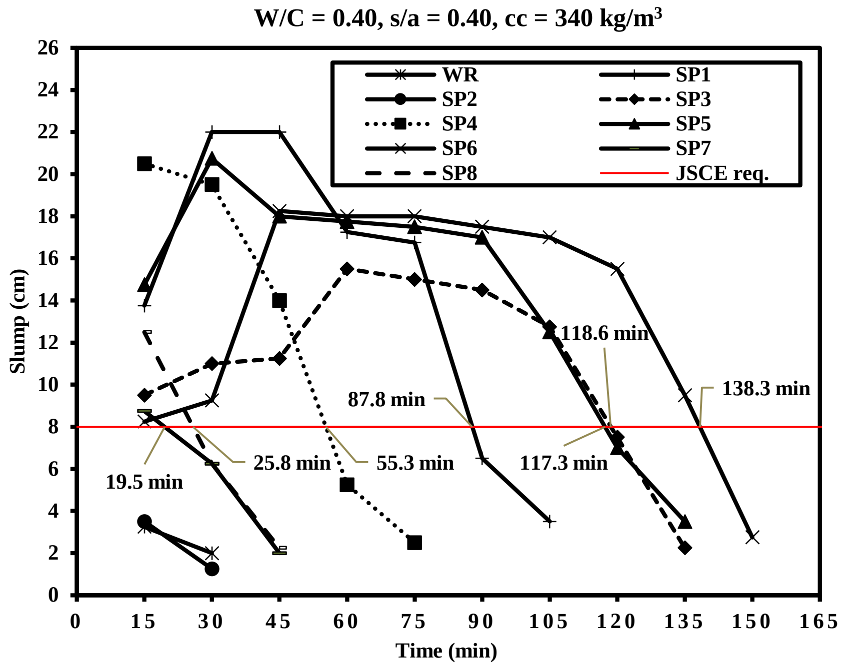

Fig. 4.2. Slump test results of Type 2 concrete mixtures

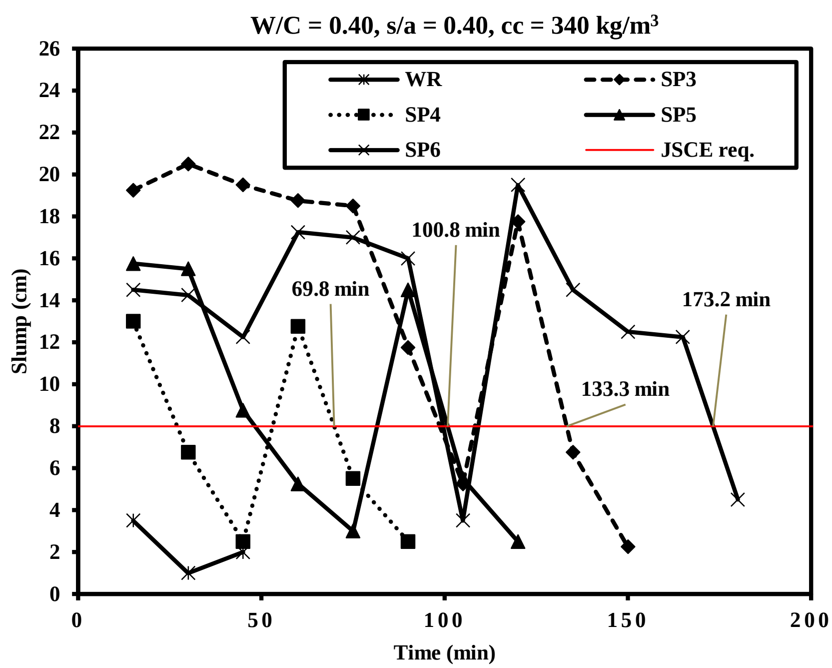

Fig. 4.3. Slump test results of Type 3 concrete mixtures

W/C = 0.40, s/a = 0.40, cc = 340 kg/m^3

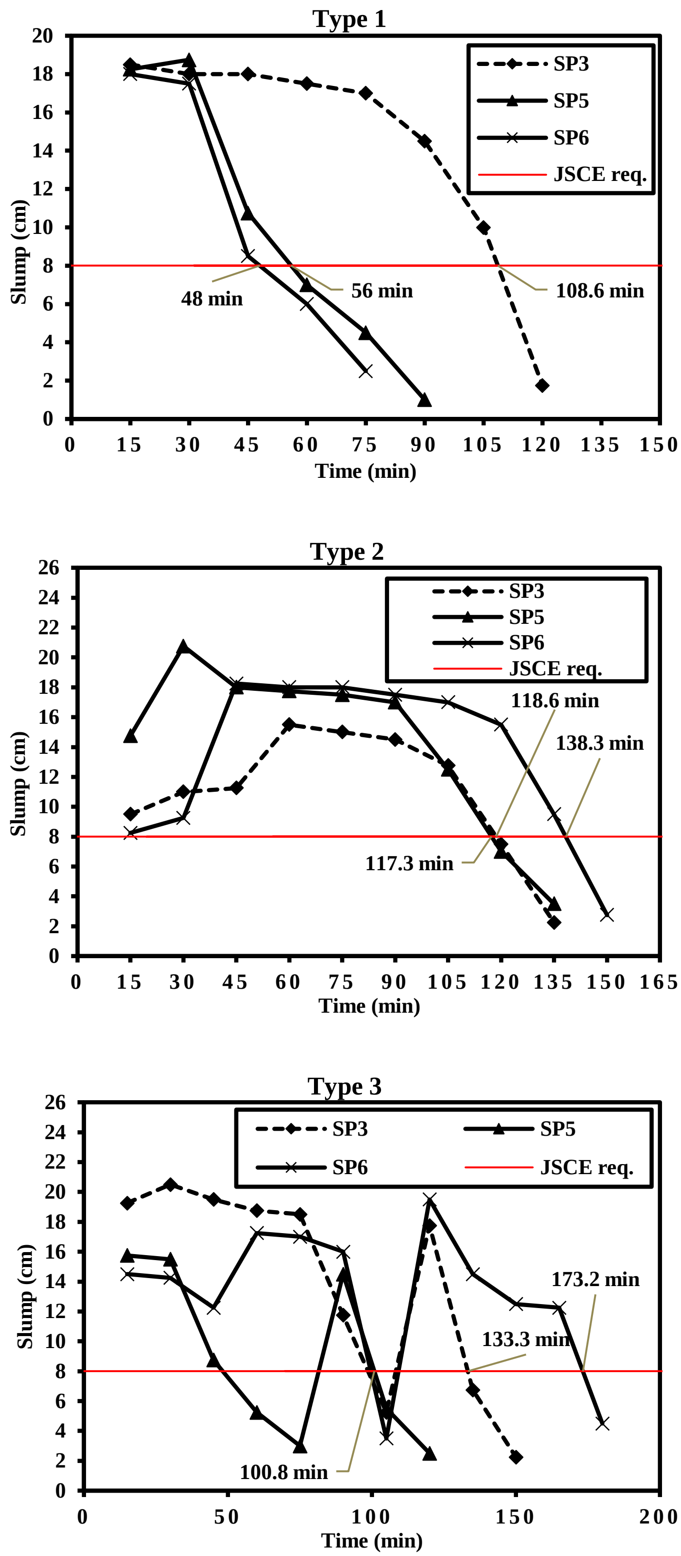

Fig. 4.4. Slump results of Types 1, 2 and 3 mixtures with best three admixtures

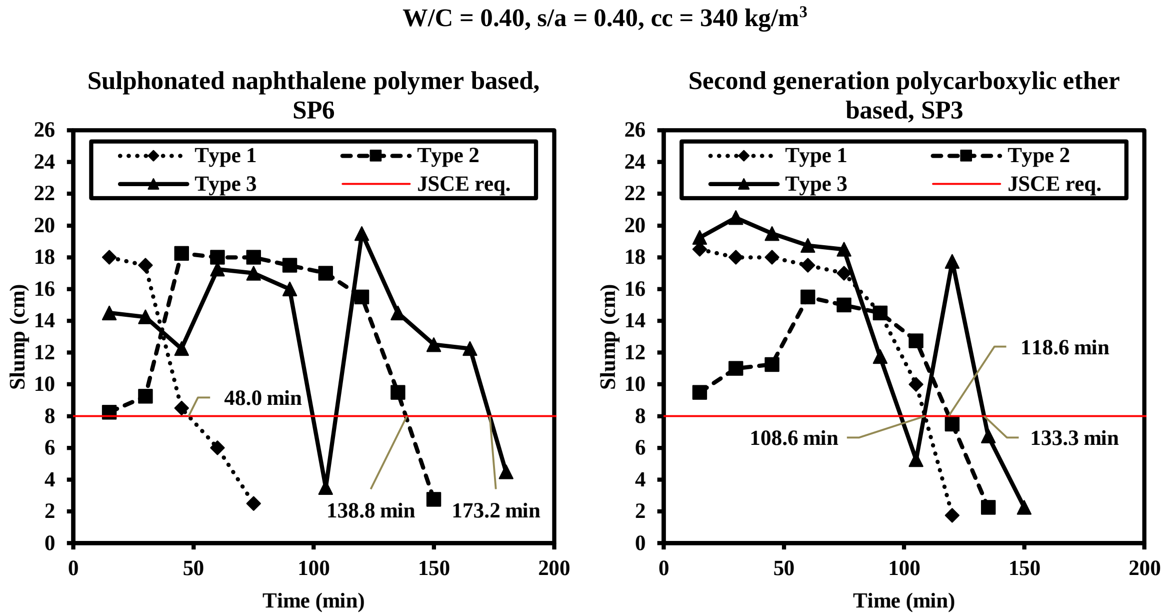

Fig. 4.5. Workability performances of SP6 and SP3 in Types 1, 2 and 3 mixtures

4.2.4 Effect of Sand to Total Aggregate Volume Ratio (s/a)

Type 4 concrete was prepared with sulphonated naphthalene polymer based superplasticizer SP6. Maximum dosage of the superplasticizer was applied in two stages as was done for Type 3 concrete. The only difference in Type 3 concrete prepared with SP6 and Type 4 concrete was that, in the latter type of concrete s/a ratio was increased from 0.4 to 0.45. **Fig. 4.6** shows that slump values of Type 4 concrete mixture were greater than 8 cm for smaller time period compared to Type 3 mixture with SP6. So, based on the obtained results, it can be said that the workability of fresh superplasticized concrete decreased when the s/a ratio was increased from 0.4 to 0.45. The reason may be attributed to the increase of cohesiveness of concrete mix with the increase of s/a (Li, 2011).

Su et al. (2002) observed different result in their investigation – when s/a ratio was increased from 0.4 to 0.45, the initial slump value increased. However, an important point should be noted that, they didn't keep the dosage of superplasticizer constant for all their cases. A slightly higher dosage of superplasticizer was used in concrete with s/a ratio 0.45 than that with s/a ratio 0.4. Again, Jau et al. (2004) recorded slump results at 15 minutes intervals and found two different effects of s/a ratio on workability of superplasticized concrete for two different W/C ratios. They observed that, in case of W/C = 0.55, the slump values recorded at 15 minutes intervals were higher for s/a = 0.55 than those for s/a = 0.5. On the other hand, in case of W/C = 0.6, apart from the initial slump value all other slump values observed at 15 minutes intervals were higher for s/a = 0.5 in comparison to s/a = 0.55. The initial slump values for s/a = 0.5 and s/a = 0.55 were equal in case of W/C = 0.6. Another study (Larrard, 1987) concluded that, workability of concrete mix increases with the increase of s/a ratio up to s/a = 0.55, and after that, workability starts to decrease with the increase of s/a.

Therefore, based on the data found in previous studies, the reason of the controversy regarding the effect of s/a ratio may be attributed to the selection of different ranges of s/a and W/C. Detailed investigation considering larger ranges of s/a and W/C can lead to a more precise understanding of the effect of s/a on workability of superplasticized concrete.

4.2.5 Effect of Cement Content

Similar to Type 4 concrete mixture, Type 5 mixture was also prepared using maximum dosage of SP6 in two stages; but in this type, cement content was increased to 380 kg per cubic meter of concrete. **Fig. 4.6** shows that, Type 5 concrete mixture gave slump values more than 8 cm for longer period compared to both Type 3 and Type 4 concrete mixtures. So the results obtained for Type 4 and Type 5 mixtures indicate that, the workability of superplasticized concrete increased with the increase of cement content. The rationale behind this phenomenon was explained by Yurdakul (2010). He mentioned, for a given W/C, workability decreases as cement content (thus paste content) decreases, because of having insufficient paste to lubricate the aggregates. Therefore, it can be understood that too low cement content in the mixture can cause reduction in the workability of fresh concrete.

4.2.6 Effect of Fresh Concrete Temperature

The mixture proportion of Type 6 concrete was same as that of Type 5 concrete. In this case also SP6 was applied in two stages. The difference between Type 6 concrete and Type 5 concrete was that, during the mixing process, temperature of Type 6 concrete mixture was kept lower in comparison to that of Type 5 concrete mixture. The process of reducing the temperature of Type 6 concrete mixture is described in **Chapter 2**. From **Fig. 4.6** it can be seen that Type 6 concrete mixture resulted better workability for longer duration in comparison to Types 3, 4 and 5 mixtures. The slump value of Type 6 concrete mixture became 8 cm at the end of 263.6 minutes. So, reducing the temperature of fresh concrete increased the workability of concrete mixture. Sampebulu' (2012), Wang et al. (2014), Munday (1976), Mailvaganam (1979) and many other researchers drew similar conclusions from their investigations.

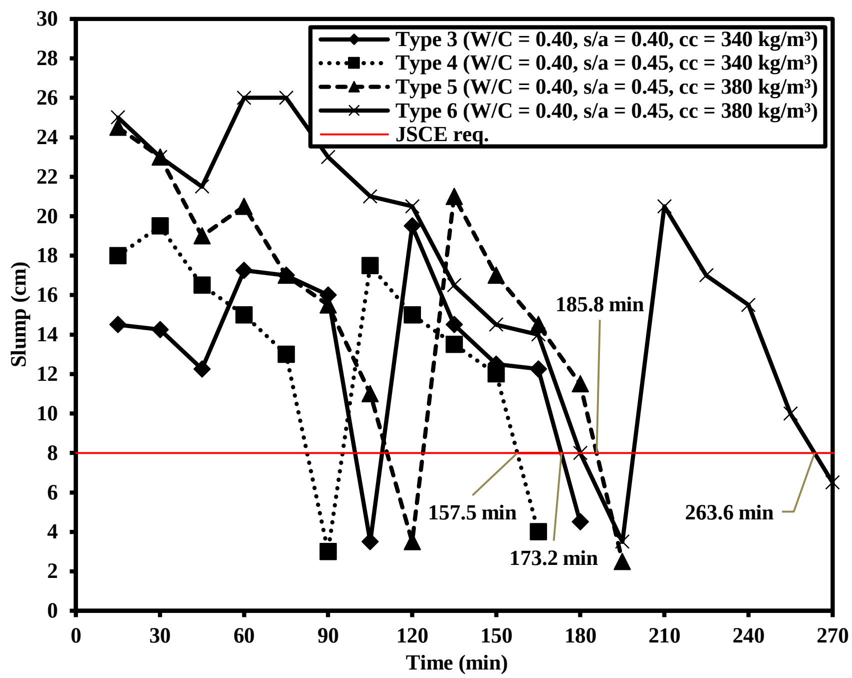

Fig. 4.6. Workability performances of Types 3, 4, 5 and 6 mixtures made with SP6

4.3 Hardened Properties of Concrete

To analyze the hardened properties of concrete made with chemical admixture, cylindrical specimens of 100 mm diameter and 200 mm length were prepared from Types 1, 2, 3, 4, 5 and 6 mixtures. The specimens were tested for determining compressive strength, splitting tensile strength and Young's modulus. Ultrasonic pulse velocities (UPV) through the specimens were also measured using Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT).

4.3.1 Effect of Types of Chemical Admixture

4.3.1.1 Compressive Strength

Fig. 4.7 shows 28 days cylindrical compressive strengths of Type 1 concrete cylinders prepared with different admixtures. Apart from the Type 1 concrete cylinders prepared with SP5, all other concrete cylinders made with chemical admixtures exhibited better compressive strengths than those exhibited by concrete cylinders made without admixture. The results therefore reapprove the findings of Mohammed and Hamada (2003), Rao and Kiran (2015), Devi and John (2014) and Alsadey (2012) as opposed to the findings of Al-Kadhimi et al. (1987) and Jerath and Yamane (1987) who concluded that the addition of superplasticizer in concrete mixture causes reduction in compressive strength. Devi and John (2014) attributed the reason of strength increase of superplasticized concrete to the improved workability of concrete in its fresh state which eventually leads to the formation of denser and less porous structure. **Fig. 4.7** shows, in comparison to other admixtures sulphonated naphthalene polymer based superplasticizer SP6 and polycarboxylic ether based superplasticizer SP3 imparted higher 28 days compressive strengths. Performances of most of the superplasticizers were better than that of the water reducer WR. The compressive strengths of concrete cylinders made with chemical admixtures were within the range of normal strength concrete specified by JSCE guideline for concrete – 2007.

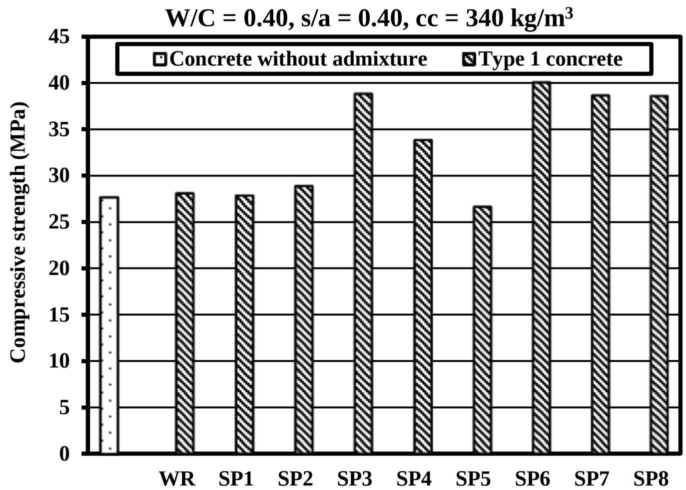

Fig. 4.7. 28 days compressive strengths of Type 1 concrete specimens

4.3.1.2 Splitting Tensile Strength

Fig. 4.8 shows, cylinders made with chemical admixtures resulted higher splitting tensile strengths than cylinders made without admixture. The results confirm the conclusions drawn by Shah et al. (2014). Polycarboxylic ether based superplasticizer SP3 resulted higher splitting tensile strength compared to other admixtures. Apart from SP2, for all other superplasticizers tensile strengths were higher than that of water reducer WR.

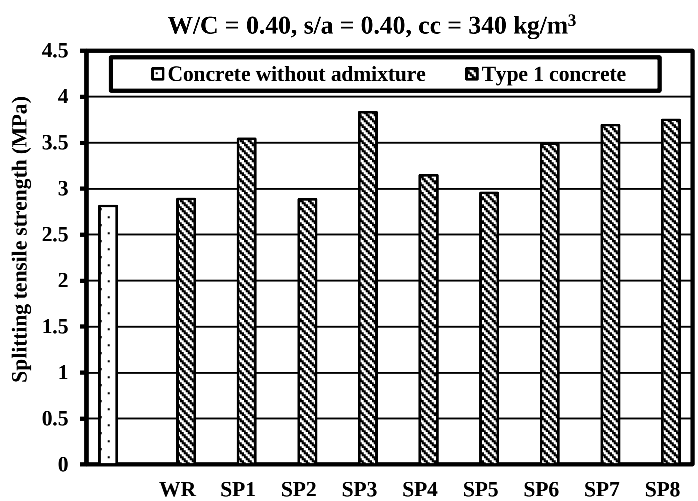

Fig. 4.8. 28 days splitting tensile strengths of Type 1 concrete specimens

4.3.1.3 Young's Modulus

The Young's moduli of Type 1 concrete cylinders are shown in **Fig. 4.9**. For cylinders made with chemical admixtures, Young's moduli were larger than that for cylinders made without admixture. So, results conform to the observation of Mohammed and Hamada (2003). In most of the cases Young's moduli of superplasticized concrete cylinders were higher compared to cylinders made with water reducer WR.

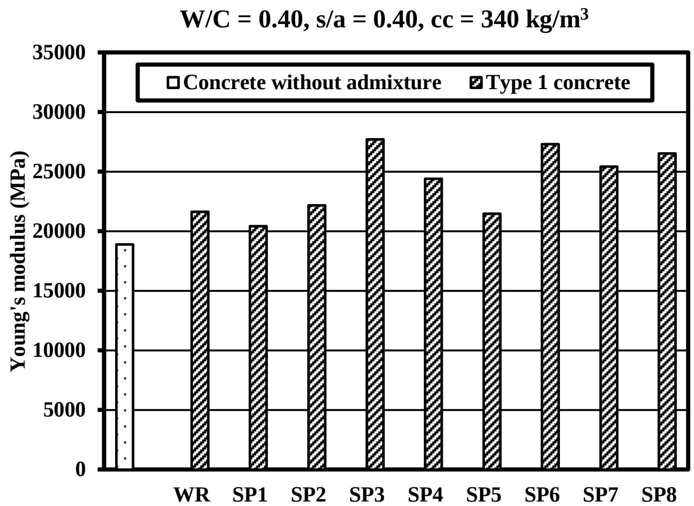

Fig. 4.9. 28 days Young's moduli of Type 1 concrete specimens

4.3.1.4 Ultrasonic Pulse Velocity (UPV)

UPV test results of Type 1 concrete cylinders prepared with different admixtures are shown in **Fig. 4.10**. Like the compressive strengths, splitting tensile strengths and Young's moduli of superplasticized concrete, in most of the cases ultrasonic pulse velocities through superplasticized concrete specimens were higher than those through concrete specimens made without admixture. Most of the superplasticizers resulted higher UPVs compared to water reducer WR. Again, ultrasonic pulse velocities through concrete specimens made with sulphonated naphthalene polymer based SP6 were higher in comparison to specimens made with other admixtures.

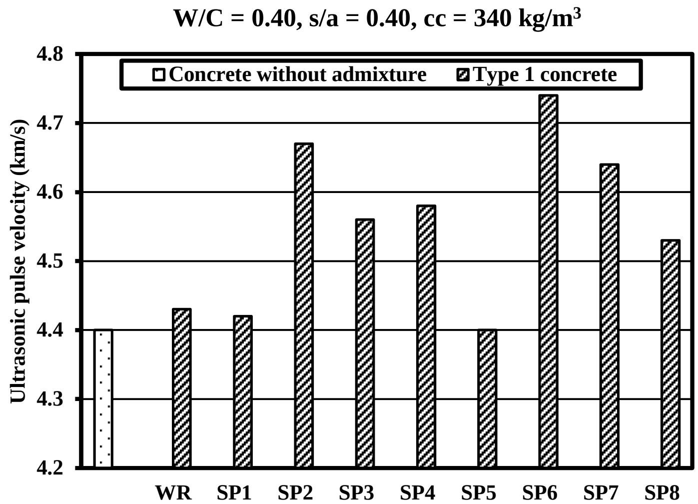

Fig. 4.10. 28 days UPV test results of Type 1 concrete specimens

4.3.2 Effect of Increased Dosage of Chemical Admixture

To understand the effect of increased dosage of chemical admixture on hardened properties of concrete, test results of cylindrical specimens made from Type 1 and Type 2 mixtures have been compared. In case of each Type 1 mixture, average of the maximum and minimum recommended dosages of admixture was used. On the other hand, in case of each Type 2 mixture, maximum recommended dosage of admixture was used. W/C, s/a and cement content were respectively 0.4, 0.4 and 340 kg/m^3 for both the cases.

4.3.2.1 Compressive Strength

28 days cylindrical compressive strengths of cylinders prepared with different dosages of admixtures are presented in **Fig. 4.11**. In most of the cases, 28 days compressive strengths increased with the increase of admixture dosages. However, it should be noted that, in all cases the dosages of admixtures were within the dosage ranges recommended by the manufacturers. In case of sulphonated naphthalene polymer based superplasticizer SP6, the compressive strength exhibited by concrete specimens with maximum admixture dosage was less than that exhibited by specimens with average

admixture dosage. All concrete mixtures with maximum dosages of admixtures (i.e. Type 2 mixtures) were subjected to longer mixing periods than those with average dosages of admixtures (i.e. Type 1 mixtures). Again, the difference between the mixing periods of the concrete mixture with average dosage of SP6 and the concrete mixture with maximum dosage of SP6 was larger compared to other admixtures (**Fig 4.1**, **Fig. 4.2**). Therefore, the reason for the drop in the strength of concrete with maximum dosage of SP6 may be attributed to the distortion in the rheological properties of fresh concrete due to prolonged mixing (Erdoğdu, 2005).

4.3.2.2 Splitting Tensile Strength

28 days splitting tensile strengths of cylinders prepared with different dosages of admixtures are presented in **Fig. 4.12**. Apart from SP3 and SP6, for all other admixtures splitting tensile strengths of cylinders increased with the increase of admixture dosages.

4.3.2.3 Young's Modulus

Fig. 4.13 shows, Young's moduli of concrete cylinders prepared with different dosages of admixtures. For WR, SP4 and SP5, Young's moduli of concrete specimens increased with the increase of admixture dosages; but for SP3 and SP6, Young's moduli decreased with the increase of admixture dosages.

4.3.2.4 Ultrasonic Pulse Velocity (UPV)

Fig. 4.14 presents the UPV test results for different dosages of chemical admixtures. For WR, SP3 and SP5 ultrasonic pulse velocities through specimens increased with the increase of admixture dosages. For SP4 and SP6, ultrasonic pulse velocities through specimens decreased when the dosages were increased to the maximum recommended limits.

W/C = 0.40, s/a = 0.40, cc = 340 kg/m³

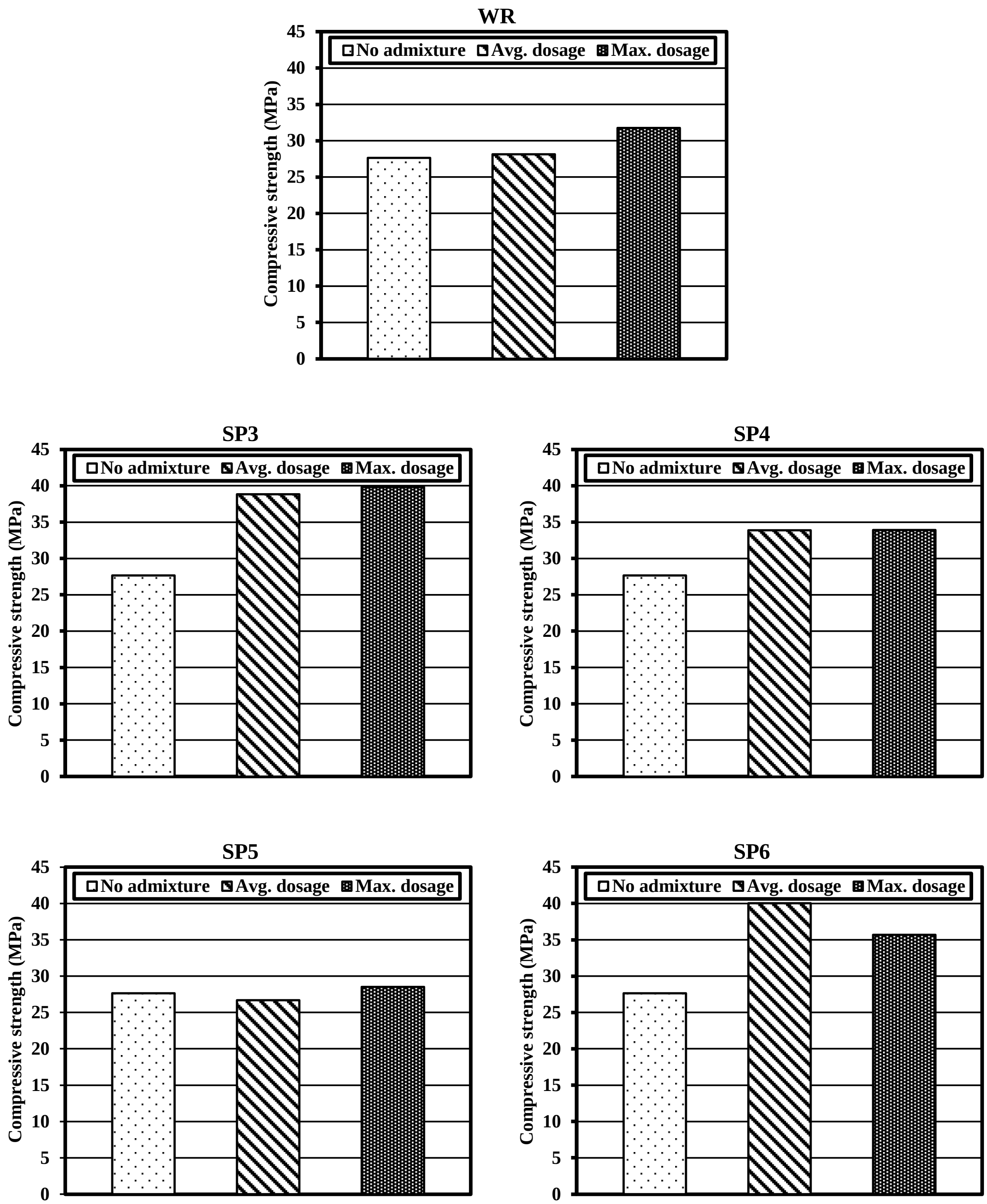

Fig. 4.11. 28 days compressive strengths for different dosages of admixtures

W/C = 0.40, s/a = 0.40, cc = 340 kg/m³

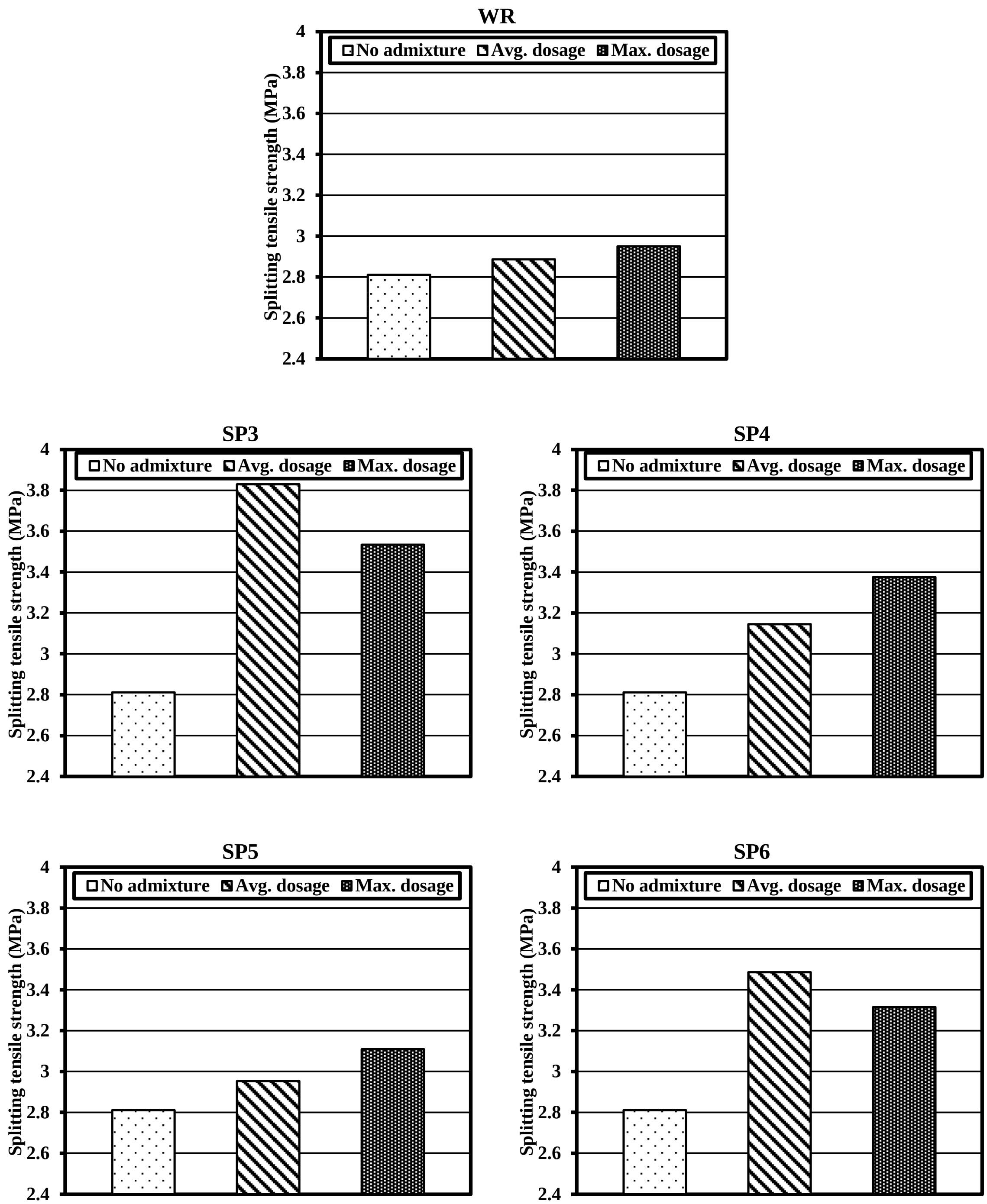

Fig. 4.12. 28 days splitting tensile strengths for different dosages of admixtures

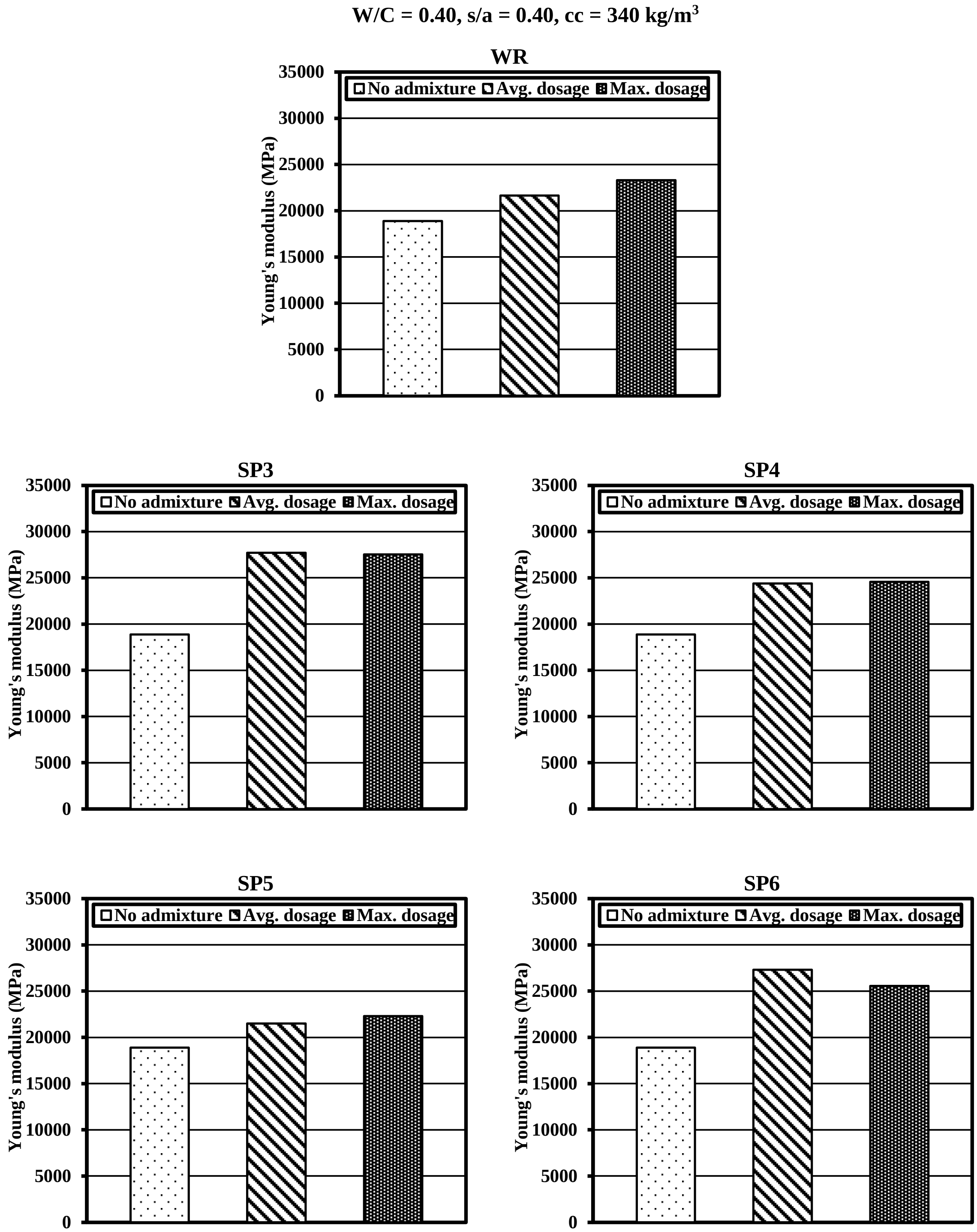

Fig. 4.13. 28 days Young's moduli for different dosages of admixtures

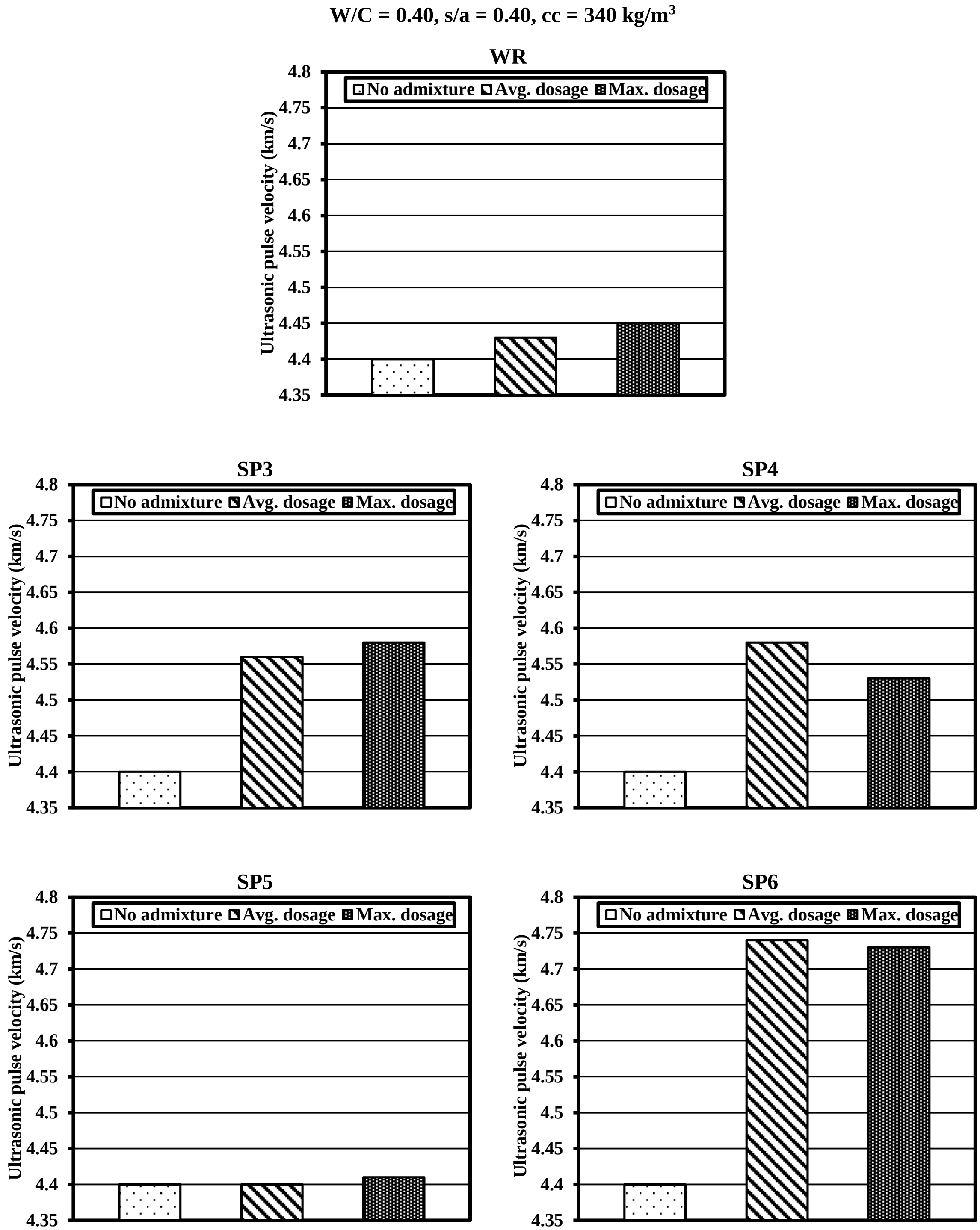

Fig. 4.14. 28 days UPV test results for different dosages of admixtures

4.3.3 Effect of Two-Stage Dosage of Chemical Admixture

Test results of Types 2, 3 concrete cylinders and cylinders without admixture have been compared to study the effect of two-stage dosage of admixture. During the preparation of each Type 2 mixture, maximum recommended dosage of admixture was applied at the beginning of mixing. While in case of each Type 3 mixture, the same dosage was applied in two stages. 2/3 of the dosage was applied at the beginning and the rest 1/3 was applied when the slump value became less than or equal to 3 cm. W/C, s/a and cement content were respectively 0.4, 0.4 and 340 kg/m^3 for both the cases.

4.3.3.1 Compressive Strength

Fig. 4.15 shows, the 28 days compressive strengths of cylindrical concrete specimens made from Type 2 and Type 3 mixtures. Type 3 concrete specimens resulted higher 28 days compressive strengths compared to the specimens without admixture. The results support the findings of Erdoğdu (2005) as opposed to the findings of Al-Kadhimi et al. (1987). Moreover, for SP4, SP5 and SP6, Type 3 concrete performed better in comparison to Type 2 concrete.

4.3.3.2 Splitting Tensile Strength

The 28 days splitting tensile strengths of cylindrical concrete specimens made from Type 2 and Type 3 mixtures are presented in **Fig. 4.16**. Type 3 concrete specimens imparted higher splitting tensile strengths compared to the specimens without admixture. For SP4 and SP6, Type 3 concrete performed better in comparison to Type 2 concrete.

4.3.3.3 Young's Modulus

Young's moduli of concrete specimens made from Type 2 and Type 3 mixtures are presented in **Fig. 4.17**. It can be seen that Young's moduli of Type 3 concrete specimens were higher in comparison to the specimens without admixture.

4.3.3.4 Ultrasonic Pulse Velocity (UPV)

Fig. 4.18 shows, UPV test results of Type 2 and Type 3 specimens. UPVs through Type 3 specimens were higher than those through the specimens without admixture.

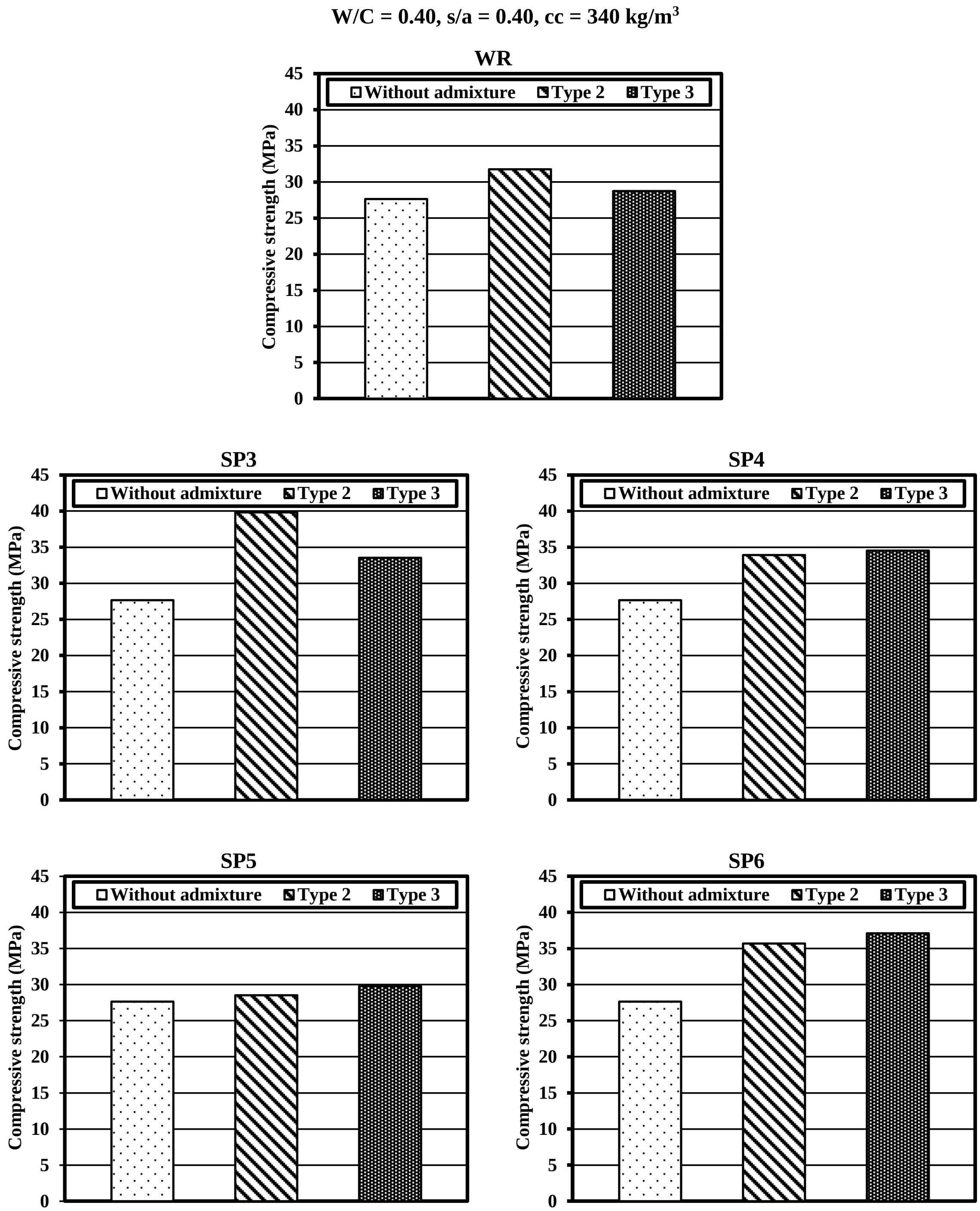

Fig. 4.15. 28 days compressive strengths of Type 2 and Type 3 concrete specimens

W/C = 0.40, s/a = 0.40, cc = 340 kg/m^3

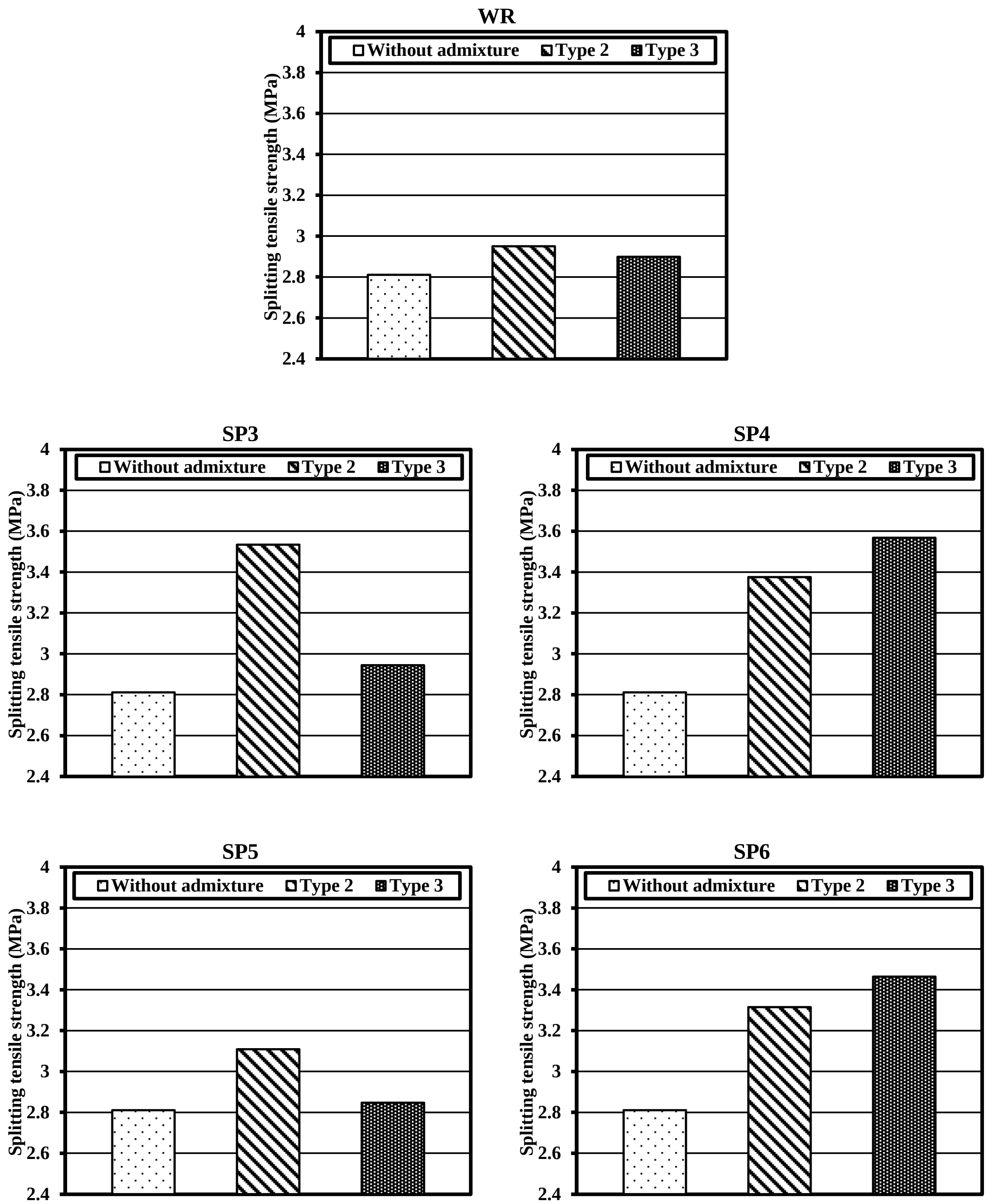

Fig. 4.16. 28 days splitting tensile strengths of Type 2 and Type 3 concrete specimens

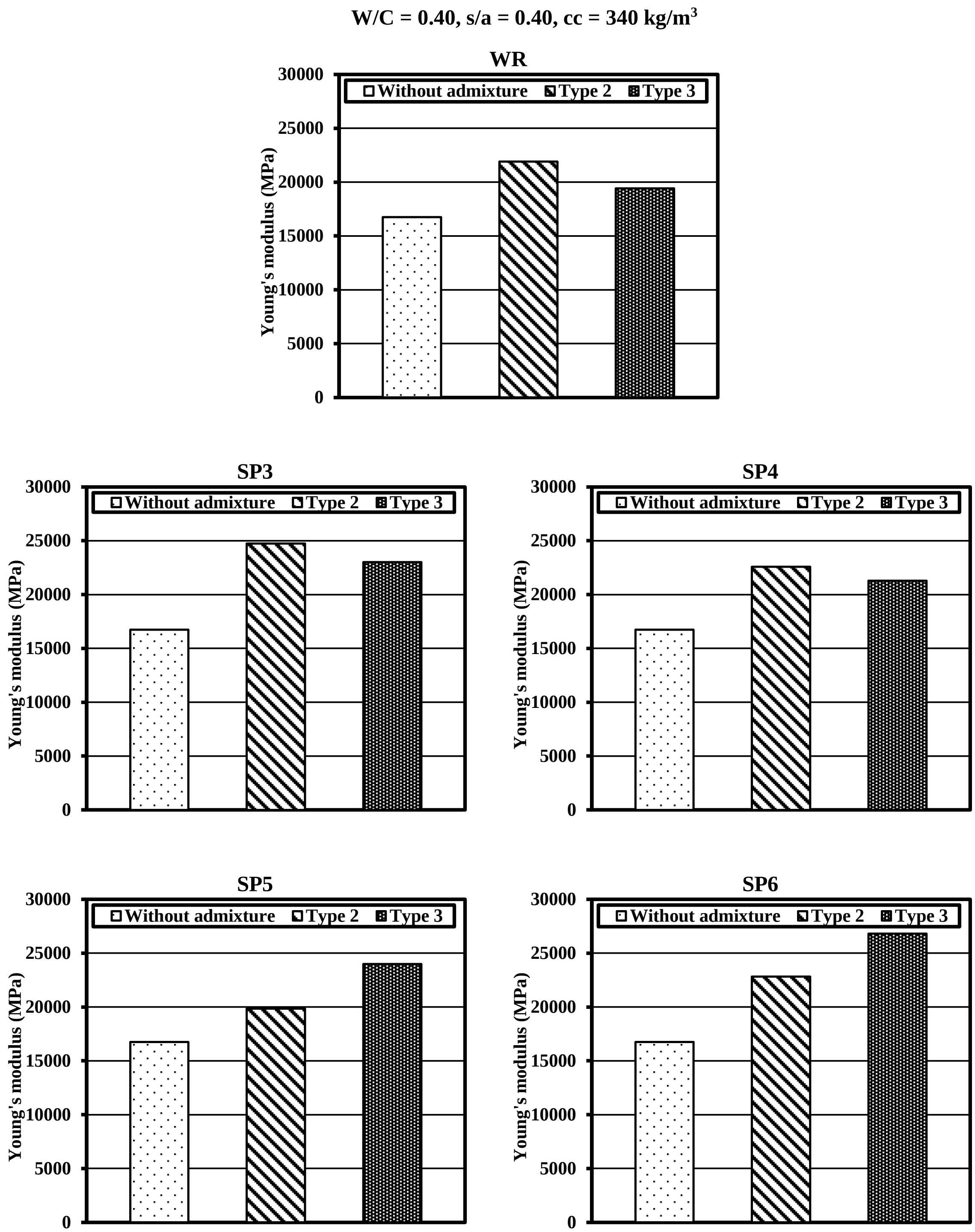

Fig. 4.17. 28 days Young's moduli of Type 2 and Type 3 concrete specimens

W/C = 0.40, s/a = 0.40, cc = 340 kg/m^3

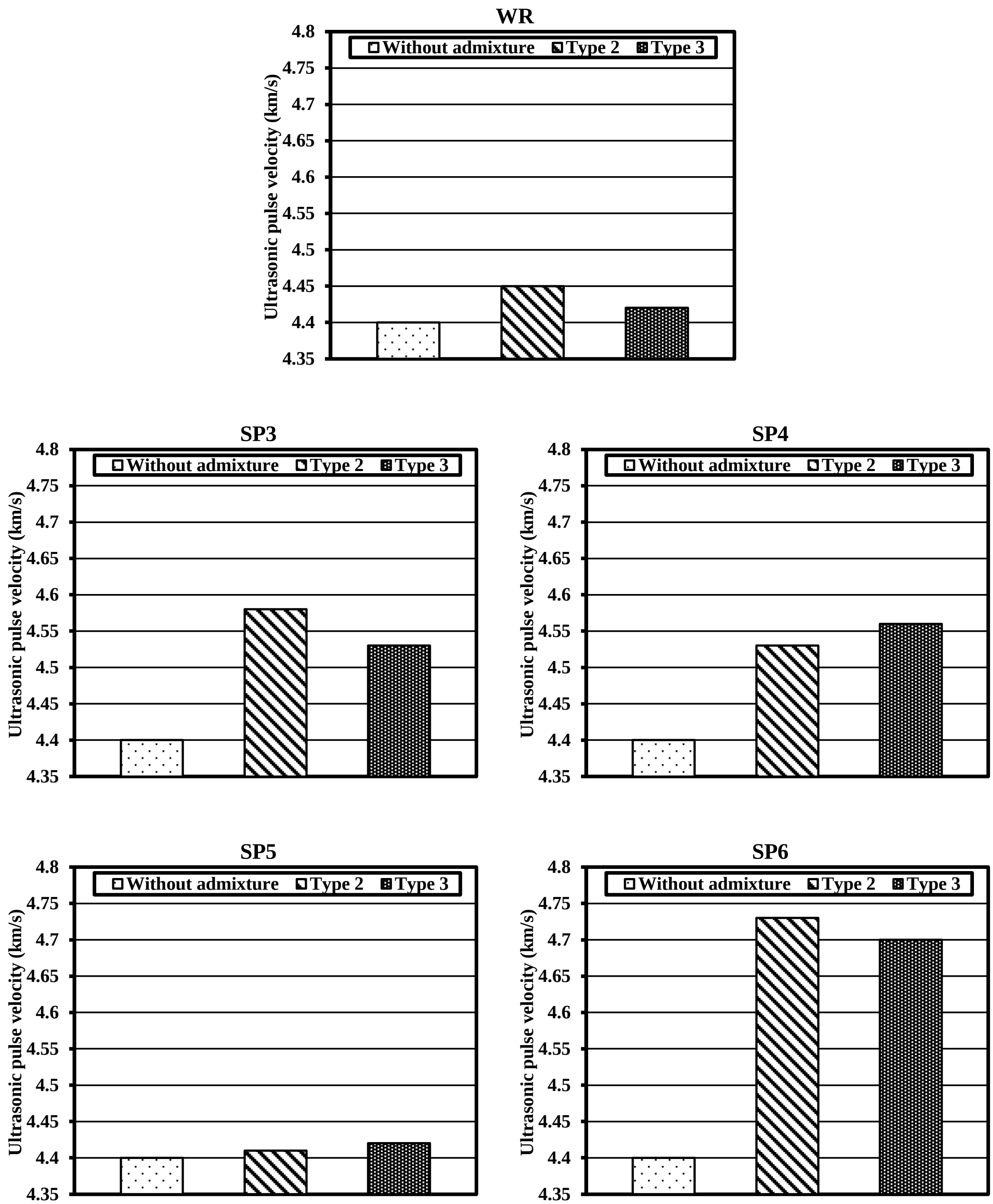

Fig. 4.18. 28 days UPVs through Type 2 and Type 3 concrete specimens

4.3.4 Effect of Sand to Total Aggregate Volume Ratio (s/a)

To identify the effect of s/a ratio on hardened properties of concrete, test results of Type 3 and Type 4 concrete specimens with SP6 have been compared. In Type 3 mixture the s/a ratio was 0.4, where in Type 4 mixture s/a was increased to 0.45. W/C and cement content were respectively 0.4 and 340 kg/m^3 for both the cases. The hardened properties of Type 3 and Type 4 concrete specimens are shown in **Fig. 4.19**.

4.3.4.1 Compressive Strength

Fig. 4.19 shows, the 28 days compressive strength of superplasticized concrete reduced when the s/a was increased from 0.4 to 0.45. The results contradict with the results observed by Jau et al. (2004). They observed that, for both W/C = 0.55 and W/C = 0.6, compressive strength of concrete with s/a ratio 0.55 was higher in comparison to compressive strength of concrete with s/a ratio 0.5. Therefore, to address this controversy more detailed investigation is required considering larger ranges of s/a and W/C.

4.3.4.2 Splitting Tensile Strength

It can be seen from **Fig. 4.19**, splitting tensile strength of superplasticized concrete decreased when the s/a was increased from 0.4 to 0.45.

4.3.4.3 Young's Modulus

Fig. 4.19 shows, Young's modulus of concrete with SP6 reduced slightly when the s/a was increased from 0.4 to 0.45.

4.3.4.4 Ultrasonic Pulse Velocity (UPV)

Fig. 4.19 shows, UPV through superplasticized concrete specimen decreased when the s/a was increased from 0.4 to 0.45.

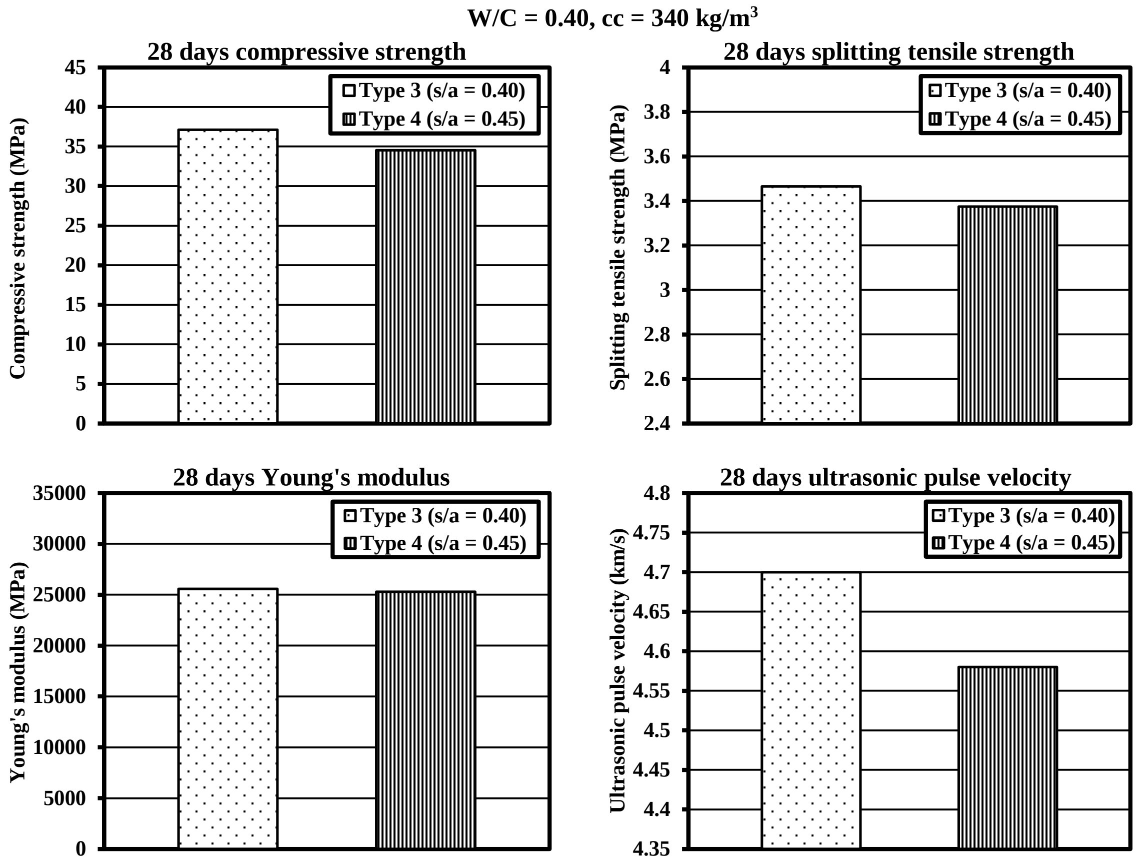

Fig. 4.19. Hardened properties of Type 3 and Type 4 concrete specimens

4.3.5 Effect of Cement Content

To understand the effect of cement content on hardened properties of concrete, test results of Type 4 and Type 5 concrete cylinders with SP6 have been compared. In Type 4 mixture the cement content was 340 kg/m^3, where in Type 5 mixture cement content was 380 kg/m^3. W/C and s/a were respectively 0.4 and 0.45 for both the cases. The hardened properties of Type 4 and Type 5 concrete cylinders are shown in **Fig. 4.20**.

4.3.5.1 Compressive Strength

Fig. 4.20 shows, the 28 days compressive strength of superplasticized concrete increased when the cement content was increased from 340 kg/m^3 to 380 kg/m^3.

4.3.5.2 Splitting Tensile Strength

It can be seen from **Fig. 4.20**, splitting tensile strength of superplasticized concrete increased when the cement content was increased from 340 kg/m^3 to 380 kg/m^3.

4.3.5.3 Young's Modulus

Fig. 4.20 shows, Young's modulus of concrete with SP6 increased when the cement content was increased from 340 kg/m^3 to 380 kg/m^3.

4.3.5.4 Ultrasonic Pulse Velocity (UPV)

Fig. 4.20 shows, UPV through superplasticized concrete specimen increased when the cement content was increased from 340 kg/m^3 to 380 kg/m^3.

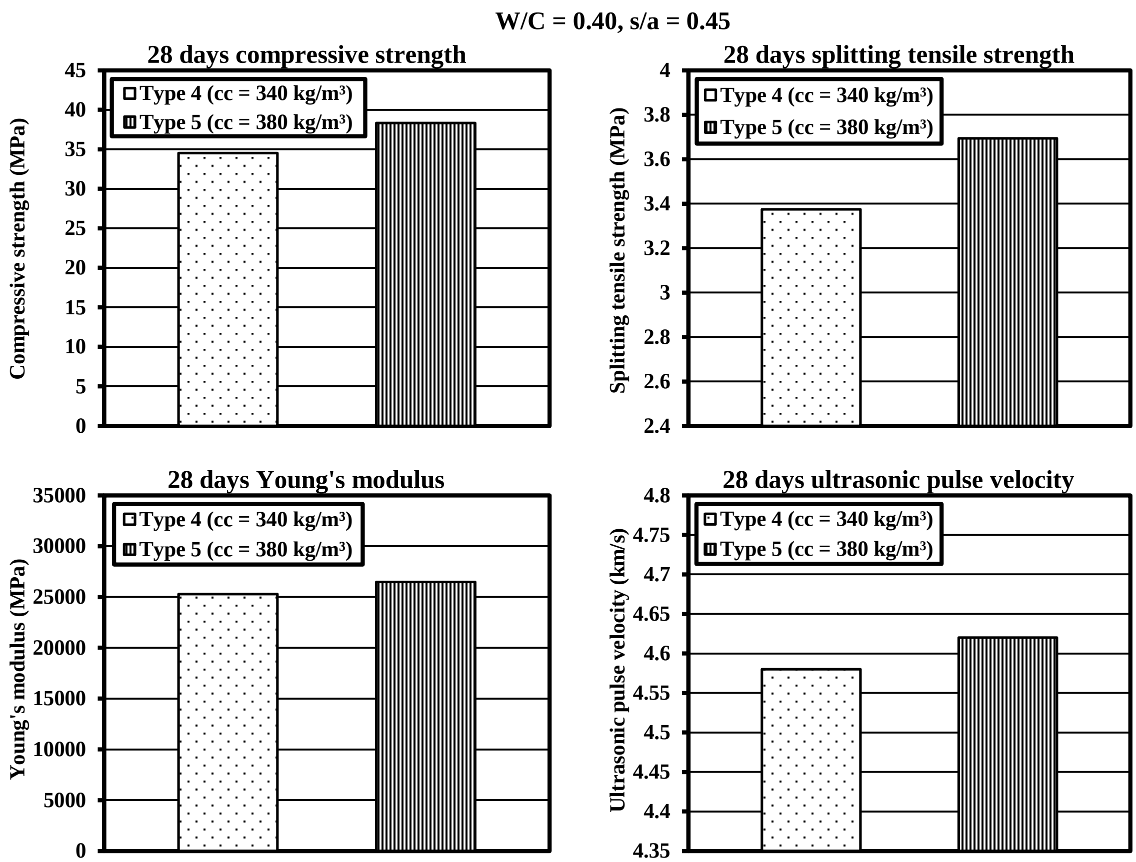

Fig. 4.20. Hardened properties of Type 4 and Type 5 concrete specimens

4.3.6 Effect of Fresh Concrete Temperature

Test results of Type 5 and Type 6 concrete cylinders with SP6 have been compared to study the effect of fresh concrete temperature on hardened properties of concrete. The mixing temperature of Type 6 mixture was kept lower compared to that of Type 5 mixture. However, the curing temperatures for both the cases were same. W/C, s/a and cement content were respectively 0.4, 0.45 and 380 kg/m^3 for both the cases.

4.3.6.1 Compressive Strength

The 7 days and 28 days compressive strengths of Type 5 and Type 6 concrete cylinders are shown in **Fig. 4.21**. The results show that, although the 7 days strengths of Type 6 concrete specimens were bit lower than those of Type 5 concrete specimens; the 28 days strengths for both the cases were almost same. Similar conclusion was drawn by Burg (1996).

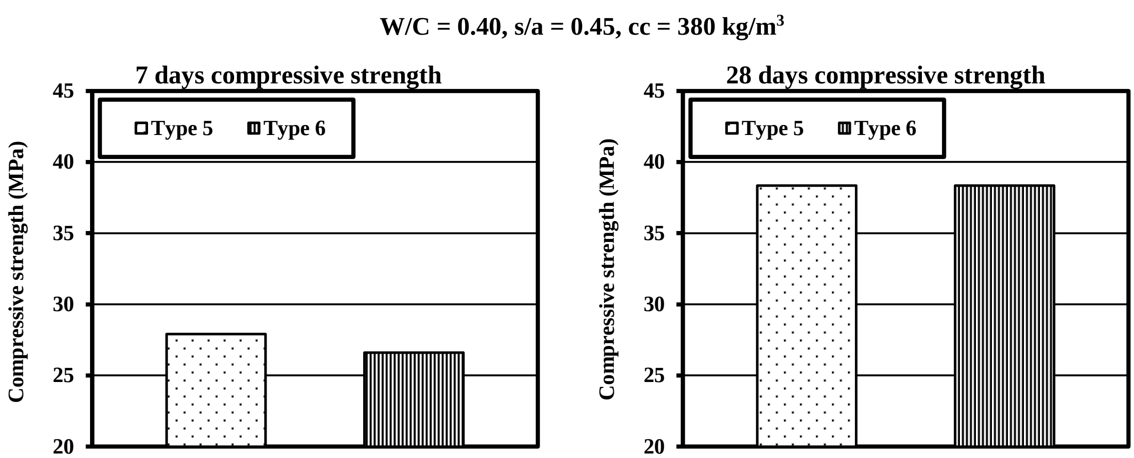

Fig. 4.21. Compressive strengths of Type 5 and Type 6 concrete specimens

4.3.6.2 Splitting Tensile Strength

Fig. 4.22 shows, the splitting tensile strengths of Type 5 and Type 6 cylinders. Splitting tensile strength of Type 5 concrete was a bit larger than that of Type 6 concrete.

4.3.6.3 Young's Modulus

Fig. 4.22 shows, the Young's moduli of Type 5 and Type 6 concrete specimens. Young's modulus of Type 6 concrete was larger in comparison to that of Type 5 concrete. However, the difference is insignificant.

4.3.6.4 Ultrasonic Pulse Velocity (UPV)

Fig. 4.22 shows, the UPV test results of Type 5 and Type 6 concrete specimens. UPVs through Type 6 concrete specimens were slightly larger compared to those through Type 5 concrete specimens.

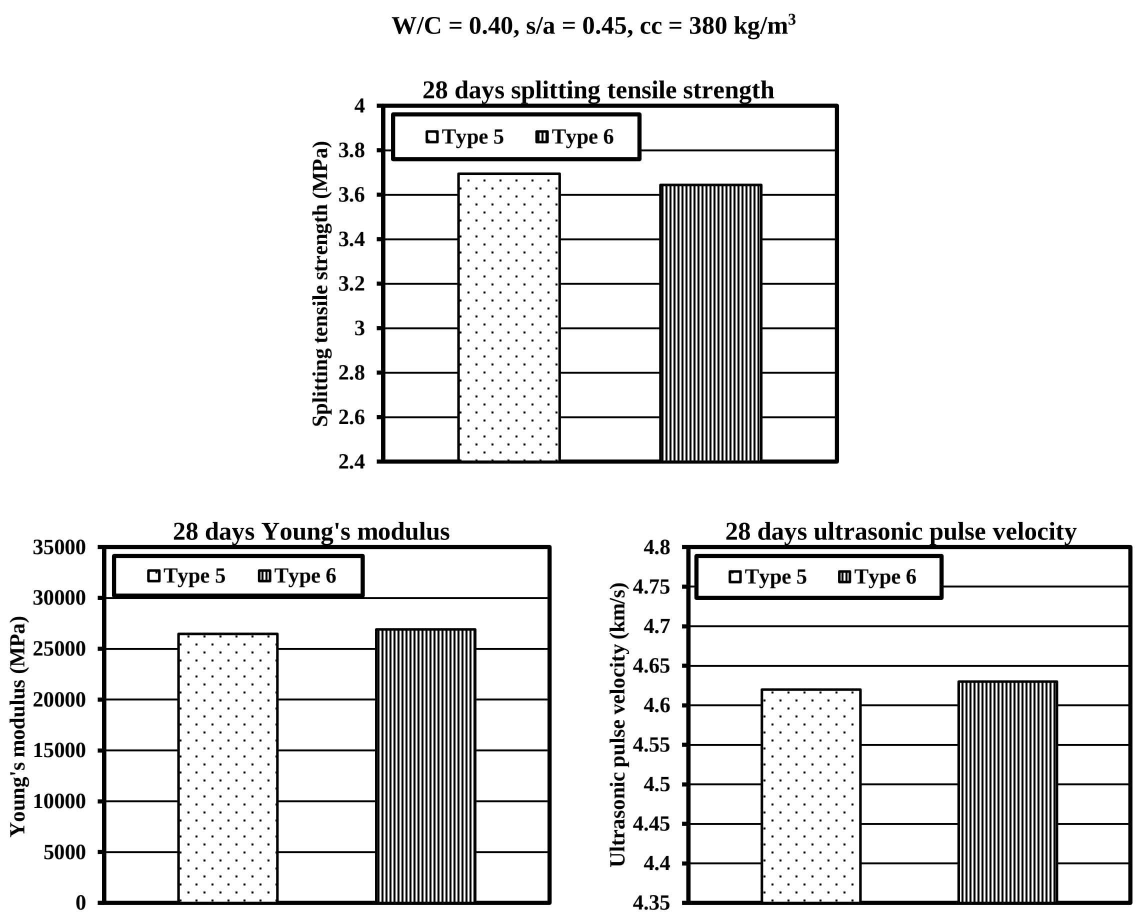

Fig. 4.22. 28 days splitting tensile strengths, Young's moduli and UPV test results of Type 5 and Type 6 concrete specimens

4.3.7 Relationship between Splitting Tensile Strength and Compressive Strength

The relationships between splitting tensile strength and compressive strength of concrete proposed in this study as well as in other studies are shown in **Fig. 4.23**. Based on the data presented in **Fig. 4.23**, the splitting tensile strength can be correlated with compressive strength by the following equation:

$$f_t = 0.567\sqrt{f_c'} \quad ; \quad R^2 = 0.65 \tag{4.1}$$

Where, f_t is splitting tensile strength in MPa and f_c' is compressive strength of superplasticized concrete in MPa. It should be noted that the compressive strength values presented in **Fig 4.23** are within the range of 26.7 MPa to 40 MPa.

The relationship between splitting tensile strength and compressive strength of concrete proposed by ACI 318 – 14 is as follows:

$$f_t = 0.556\sqrt{f_c'} \tag{4.2}$$

Again, ACI Committee 363 proposed the following equation to correlate the splitting tensile strength and the compressive strength of high-strength concrete:

$$f_t = 0.59\sqrt{f_c'} \tag{4.3}$$

Both equations (4.1) and (4.2) suggest that the relation proposed by ACI Committee 363 slightly overestimates the value of splitting tensile strength when the compressive strength of concrete is less than 40 MPa.

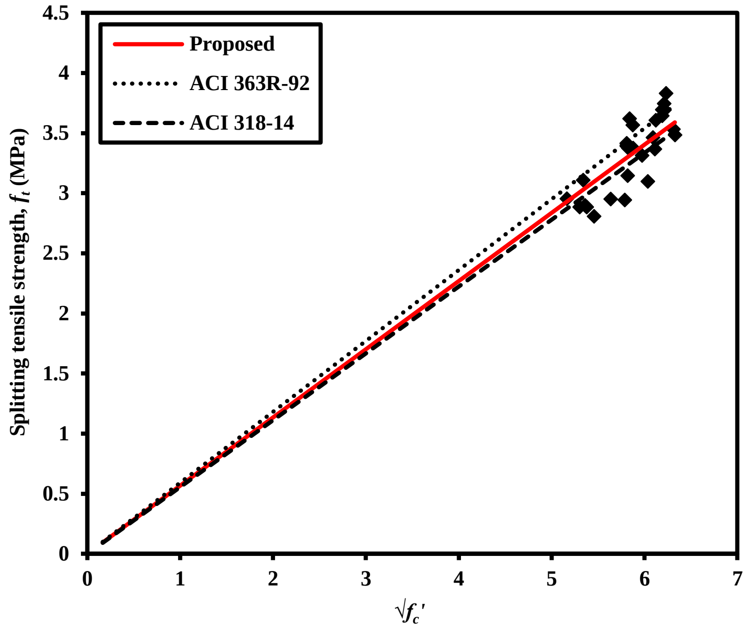

Fig. 4.23. Relationship between splitting tensile strength and compressive strength

4.3.8 Relationship between Young's Modulus and Compressive Strength

Fig. 4.24 shows relationships between Young's modulus and square root of compressive strength of concrete according to different studies. Based on the data presented in **Fig. 4.24**, the relationship between Young's modulus and compressive strength of normal-weight superplasticized concrete is proposed as following:

$$E_c = 4304.3\sqrt{f_c'} \quad ; \qquad R^2 = 0.66 \tag{4.4}$$

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

ACI 318 – 14 proposed the following relation between Young's modulus and compressive strength for both normal-weight concrete and lightweight concrete:

$$E_c = 4732\sqrt{f_c'} \tag{4.5}$$

It can be seen that, the coefficient of $\sqrt{f_c'}$ proposed by ACI 318 – 14 is higher compared to that proposed in this study.

Again, Carrasquillo et al. (1981) and Shih et al. (1989) proposed equations (4.6) and (4.7) respectively for normal-weight concrete.

$$E_c = 3320\sqrt{f_c'} + 6900 \tag{4.6}$$

$$E_c = 4660\sqrt{f_c'} - 1370 \tag{4.7}$$

Equation (4.6) suggests that the relation proposed by ACI 318 – 14 overestimates the Young's moduli of concrete specimens with compressive strengths over 25 MPa. Moreover, comparing equation (4.5) with equation (4.7) it can be seen that, for all strength grades ACI 318 – 14 relation gives higher values of Young's moduli compared to equation (4.7). The relation proposed in this study gives values of Young's moduli which are very close to those predicted by the relation proposed by Shih et al. (1989).

Shih et al. (1989) figured out the reason of discrepancy between their relation and that proposed by ACI 318 – 14. The ACI 318 – 14 relation between Young's modulus and compressive strength of concrete was originally recommended by Pauw (1960), based mainly on experimental data of lightweight concrete along with normal-weight concrete for the purpose of comparison. For reasons of simplicity and the lack of sufficient data at that time, Pauw (1960) suggested one formula for predicting Young's modulus for both lightweight concrete and normal-weight concrete. According to Mehta (1986) the Young's modulus of concrete is influenced by many factors such as moisture state of the specimen, loading conditions and loading rate, Young's modulus of cement-paste matrix, porosity and composition of the transition zone, Young's modulus of the aggregate, volume fracture etc. Therefore, it is more appropriate to use different relations for predicting Young's moduli of normal-weight concrete and lightweight concrete.

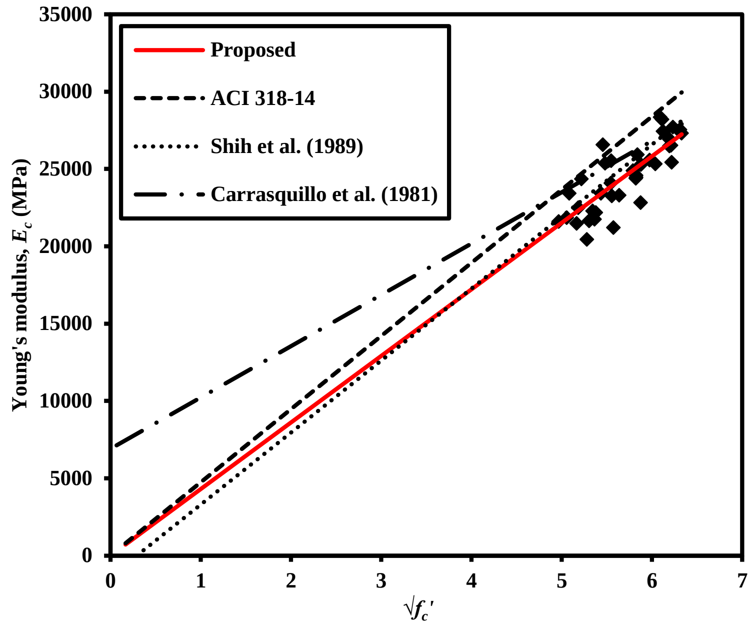

Fig. 4.24. Relationship between Young's modulus and compressive strength

4.3.9 Relationship between Compressive Strength and UPV

Fig. 4.25 shows relationships between compressive strength of concrete and ultrasonic pulse velocity (UPV) according to different researchers. Based on the experimental data presented in **Fig 4.25**, the following relationship is proposed to correlate UPV with compressive strength of superplasticized concrete:

$$f_c' = 0.0865e^{1.3164UPV} \quad ; \quad R^2 = 0.81 \qquad (4.8)$$

Where, *UPV* is ultrasonic pulse velocity in km/s and f_c' is compressive strength of superplasticized concrete in MPa.

Over decades, several relationships between UPV and compressive strength have been proposed for normal density concrete. Sturrup et al. (1984) proposed a logarithmic relationship, while Ben-Zeitun (1986) suggested linear relationship. However, exponential relationships are the most common ones. For instance, Klieger (1957), Ravindrarajah et al. (1988) and Trtnik et al. (2009) proposed following equations respectively to correlate UPV with compressive strength of concrete:

$$f_c' = 0.0141e^{0.0017UPV} \qquad (4.9)$$

$$f_c' = 0.06e^{0.00144UPV} \qquad (4.10)$$

$$f_c' = 0.0854e^{1.2882UPV} \qquad (4.11)$$

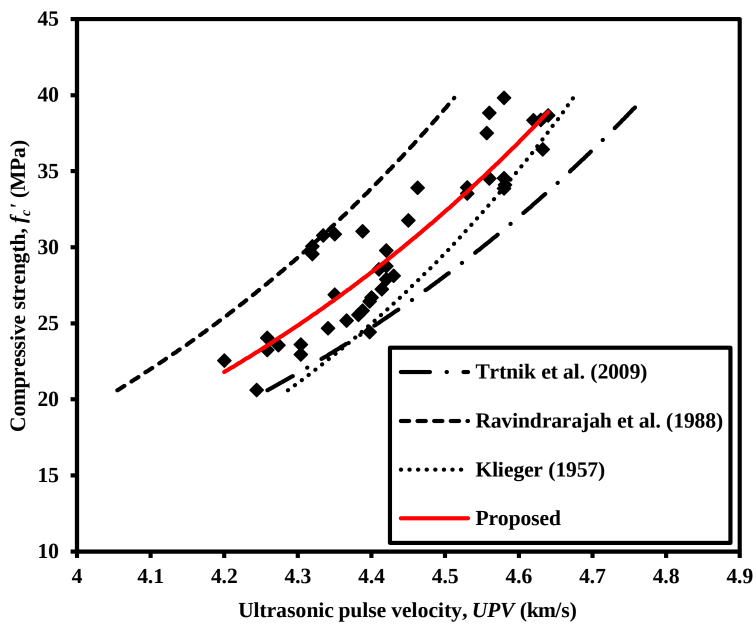

Fig. 4.25. Relationship between and compressive strength and ultrasonic pulse velocity (UPV)

4.4 Cost Analysis of Concrete with Chemical Admixture

Costs of 1 m^3 of concrete mixtures made with maximum recommended dosages of different chemical admixtures and cost of 1 m^3 of mixture made without admixture are shown in **Fig. 4.26**. It should be noted that the costs presented in **Fig. 4.26** were calculated based on the local costs of materials used per m^3 of concrete. It can be seen that the cost per cubic meter of concrete made with each chemical admixture is higher compared to the concrete prepared without admixture. Lignosulphonate based water reducer WR seems to be more economical than other admixtures. On the other hand, second generation polycarboxylic ether based superplasticizer SP3 seems to be the most expensive one.

Because of high workability and pumpability for long duration, the costs related to placement and compaction of concrete with admixture will be lower in comparison to conventional concrete. Again, the final strength values of mixtures with admixtures and mixture without admixture are also different. Therefore, the cost per unit 28 days compressive strength (1 MPa) of 1 m^3 of each mixture was calculated and is presented in **Fig. 4.27**. It can be seen that, when the compressive strengths of the mixtures were taken into account most of the concrete mixtures with admixtures are found to be more economical compared to mixture without admixture. Second generation polycarboxylic ether based superplasticizer SP3 is found to be the most economical admixture.

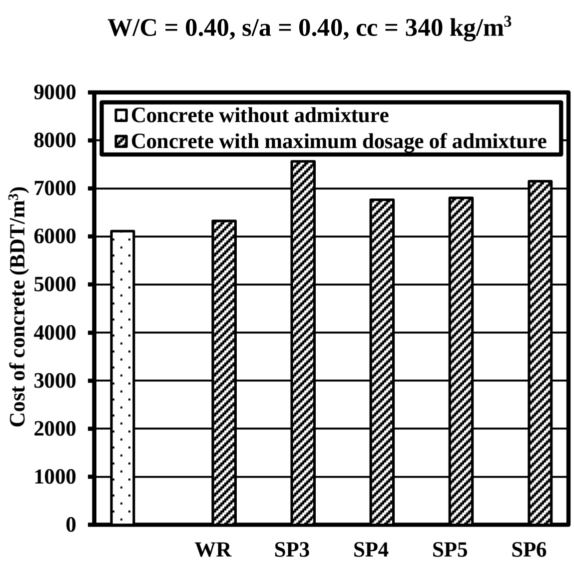

Fig. 4.26. Costs of 1 m^3 of concrete mixtures

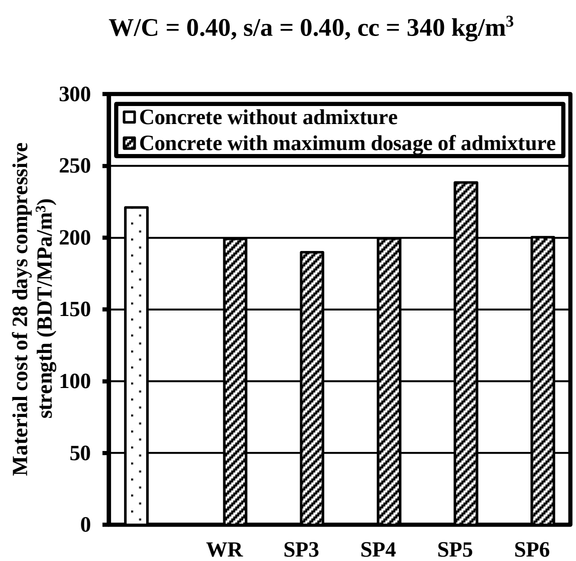

Fig. 4.27. Unit strength material costs of concrete mixtures

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 guideline for future work 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. Sulphonated naphthalene polymer based superplasticizer shows best performance in improving workability of fresh concrete in comparison to other chemical admixtures. Sulphonated naphthalene polymer based superplasticizer also helps concrete to remain workable for longer time period than others. Second generation polycarboxylic ether based superplasticizer can be categorized as the second best chemical admixture in improving workability of fresh concrete.
2. Concrete made with sulphonated naphthalene polymer based superplasticizer or second generation polycarboxylic ether based superplasticizer exhibits higher compressive strength, splitting tensile strength and Young's modulus than concrete prepared with other admixture.
3. Superplasticizers show better performance in improving fresh and hardened behaviors of concrete compared to water reducers.

4. The compressive strength of concrete increases with increase of admixture dosage, when dosage of admixture is within the range recommended by the manufacturer.
5. Applying dosage of chemical admixture in two stages helps to keep concrete workable for longer duration compared to applying the same dosage of admixture at the beginning of mixing process.
6. Concrete retempered with chemical admixture exhibits better workability and attains higher strength in comparison to concrete without admixture.
7. UPV through concrete with admixture is higher than UPV through concrete without admixture.
8. For a given W/C ratio, workability of superplasticized concrete increases with the increase of cement content.
9. If the temperature of fresh concrete is reduced during the mixing process, then it remains workable for larger period in comparison to the concrete with ambient temperature.
10. Reducing the temperature of fresh concrete during mixing process causes reduction in early concrete strength but the long term compressive strength, splitting tensile strength and Young's modulus remain unaffected.
11. Cost per unit compressive strength of concrete made with second generation polycarboxylic ether based admixture is lower compared to other admixtures.
12. Relationships between Young's modulus and compressive strength; splitting tensile strength and compressive strength; and compressive strength and UPV of superplasticized concrete are proposed.

5.3 Recommendations

When it takes too long time to haul ready mix concrete from plant to the construction site then it is recommended to apply the dosage of superplasticizer in two stages rather than applying the entire dosage at a time. The maximum dosage of superplasticizer specified by manufacturer is suggested to use to achieve maximum workability. The dosage of admixture should be within the dosage range recommended by manufacturer to ensure best strength performance. In summer, apart from adding superplasticizer in the concrete mix, it is highly recommended to use ice partially with water and to use chilled coarse aggregates to keep concrete workable for longer duration.

Moreover, ultrasonic pulse velocity (UPV) test can be conducted on structural members made with superplasticized ready mix concrete and the results can be used to evaluate the concrete compressive strength using the proposed relationship in this study.

5.4 Limitations and Future Work

One specific cement brand was used for casting of all the 297 cylinders. Chemical admixtures were collected from two companies. The cement bags were stored for 3 months. However, the bags were wrapped with plastic bags to avoid direct exposure to the atmosphere.

Though this study was primarily planned to study the effects of chemical admixtures on fresh and hardened properties of concrete, later on the scope was enhanced to investigate the effects of varying s/a ratio and cement content on fresh and hardened properties of superplasticized concrete. However, the variation of s/a ratio was limited to only two cases, s/a = 0.4 and s/a = 0.45. Therefore, any optimum s/a ratio could not be determined for which workability and compressive strength of superplasticized concrete would be maximum. Similarly, the variation of cement content was limited to 340 kg/m^3 and 380 kg/m^3.

Future works can be planned to study the effects of s/a ratio and cement content variations to find out an optimum s/a ratio and cement content for superplasticized concrete. The scope of the research can be expanded to study the effects of admixtures on modulus of rupture of concrete, flexural and shear behavior of concrete as well.

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