Effects of Glass Powder as a Partial Cement Replacement on Mechanical Properties and Behaviour of Concrete

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ABSTRACT

Concrete is the most used construction material all over the world and cement as the most valuable component in concrete affects both concrete price and quality. On the other hand, cement manufacturing industry is one of the carbon dioxide producing sources, that is caused global warming. However, using the waste materials and by-products as cement replacement materials become an attractive alternative because it helps to reduce the cost of concrete and cement manufacturing, also has numerous indirect benefits such as saving energy, reducing landfill cost and protecting the environment from possible pollution effects. Nowadays, waste glass is one of the most polluting waste materials for the world environment. For this reason, in this thesis, the glass powder (GP) of waste glass was examined as a partial cement replacement material in concrete with five different proportions (0%, 10%, 20%, 30% and 40%) for three water-binder ratios (w/b) (0.4, 0.5 and 0.6). Finally, experimental results indicated that GP can be used as a cement replacement material and it can improve both physical and mechanical properties of concrete for all three different w/b tested in this study.

Keywords: Cement replacement materials, Mechanical properties, Waste glass powder, Water-binder ratio, Workability

ÖZ

Beton, dünya genelinde en çok kullanılan yapı malzemesidir. Çimento ise betonun en önemli bileşiği olup hem betonun kalitesini hem de fiyatını önemli ölçüde etkilemektedir. Diğer taraftan, çimento üretimi endüstrisi karbon dioksit salınımının önemli bir kaynağı olup, küresel ısınmayı arttırmaktadır. Fakat, çimento yerine kısmen de olsa atık malzemelerin kullanılabilmesi önemli bir alternative olup; hem çimentonun dolayısıyle betonun fiyatını düşürecek, daha az enerji tüketilecek, atık malzemeler doğada kalmayacak ve de hava kirliliği azalacaktır. Günümüzde, atık cam bu amaç için kullanılabilecek malzemelerden biri olup hava kirliliğini azaltmaktadır. Bu nedenle, atık camdan elde edilmiş cam tozu; üç farklı su/çimento oranında (0.4, 0.5 and 0.6) üretilmiş beton için, beş değişik oranda (0%, 10%, 20%, 30% and 40%) kısmen çimento yerine kullanılmıştır. Deney neticeleri göstermiştir ki, cam tozunun kısmen çimento yerine kullanılması betonun hem fiziksel hem de mekanik özeliklerini arttırmaktadır. Sonuç olarak cam tozunun kısmen çimento yerine kullanılmasının bu çalışmada denenmiş olan üç farklı su/çimento oranlarındaki betonlar için avantajlı olduğu kanısına varılmıştır.

Anahtar Kelimeler: Çimento yerine kullanılacak malzeme, Mekanik özelikler, Atık cam tozu, su-bağlayıcı oranı, İşlenebilirlik

DEDICATION

In all my heart, I dedicate this thesis to all my family

My valuable Parents and my lovely Sisters and Brothers

I would like to thank

My lovely wife who all time encourage me for getting more success

&

My lovable brothers, Mr. Hiwa and Dr. Pshtiwan whom all time support me

&

My lovable son Mahyar

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LIST OF SYMBOLS AND ABBREVIATIONS

GP	Glass Powder
C	Cement
W	Water
w/b	Water-binder ratio
E	Modulus of elasticity
ITZ	Interfacial Transition Zone
ASR	Alkali Silica Reaction
CA	Coarse Aggregates
FA	Fine Aggregates

Chapter 1

INTRODUCTION

1.1 Background of the Study

These days, concrete is most commonly used structural material all over the world, it is a composite material which is made with mixing cement, water, and fine and coarse aggregates. Moreover, admixtures added to concrete matrix to achieve special properties. In concrete mixes, the active part which consists of cement and water is filling the voids and cementing the inert part (fine and coarse aggregate) particles together (Gambhir, 1995).

The recycling of waste materials especially waste glass material is a major problem for municipalities all over the world. The daily uses of glass products have increased seriously, resulting in large amounts of waste glass and every year plenty million tons of waste glass are land-fill in everywhere. For example, in the United States only in 2005, approximately 12.8 million tons of waste glass was disposed, while only 2.75 million tons was recycled (Schwarz, Cam & Neithalath, 2008).

Using waste glass as a construction material is an attractive option, because of the large quantity requirement and widespread sites of construction. The main applications include a partial replacement for both fine and coarse aggregate and also as a partial cement replacement in concrete matrix. Recently, using of waste glass in concrete as a partial replacement of cement or an aggregate is focused by many studies (Bhat & Rao, 2014; Vijayakumar et al, 2013).

As mentioned above, waste glass can be used in concrete, because of its chemical composition such as large quantities of silicon. When glass finely grind to powder, becomes excellent filler and may have sufficient pozzolanic properties to serve as partial cement replacement. Moreover, because of using GP in concretes the effects of alkali silica reactions appear to be reduced, while, pozzolanic reactions increase. For instance, glass powder can be used as a cement replacement material up to particle sizes less than 75 μm to prevent alkali silica reactions (Vijayakumar et al, 2013).

1.2 Problem Statement

Cement manufacturing industry is one of the carbon dioxide producing sources, where global cement manufacturing contributes about 7% of greenhouse gas emission that is caused global warming. In addition, million tons of waste glass dispose annually in everywhere, which contributes to land pollution and global worming as well (Mirzahosseini & Riding, 2015). Furthermore, the high cost requirement for cement production, contributes raising the final cost of construction projects, specially the projects which need high quality concrete; because concrete is the main construction material in construction projects and also cement is the main material in concrete matrix.

1.3 Significance of the Study

It is important to find out the best way of utilizing glass powder as a partial cement replacement in mortar and concrete production. This utilization serves construction industries and world environment in several sides. First, it releases environment from disposal materials that result in environmental pollution, which is the main risk to the environment. Second, reduces the total cement consumption, hence the emission of CO_2 will reduce, which is a serious problem in the world due to the greenhouse effects. Third, reduces the total cost requirement for construction projects, because cost request for producing cement is much higher than producing powder from waste glass. On top of these, using waste glass in concrete improves both the physical (workability and water absorption capacity) and mechanical properties (compressive strength, tensile strength, modulus of elasticity and microcracking behaviors) of concrete. The importance of this study is to estimate the effects of five different proportions of GP replacement to cement, incorporated with three different w/b ratios on physical and mechanical properties of concrete. Here, it is important to note with which combination maximum improvement could be achieved.

1.4 Objective of the Study

The aim of this study is to investigate the effects of partial replacement of glass powder to cement, on physical and mechanical properties of three different w/b concretes. The objectives to be achieved are:

1- Determining the effects of Waste Glass Powder (GP) on fresh concrete properties at different w/b ratios.
2- Studying the influence of finely divided GP (<90 μm) on concrete compressive strength, splitting tensile strength, elastic modulus and water absorption capacity at different w/b.
3- Studying the influence of glass powder addition on stress-strain curves at different w/b.
4- Determining the optimum amount of cement replacement by GP for different w/b.

5- Make conclusions and recommendations for future studies from the outcome of the study.

1.5 Outline of the Study

This study is organized into six chapters as follow:

Chapter one introduces the thesis and all components of the study and in chapter two theoretical background of the study is presented. Chapter three contains literature review. The material and experimental procedure description is represented in chapter four, and the last two chapters show analysis of the results and discussions, and conclusions of the study.

Chapter 2

THEORETICAL BACKGRAUND OF THE STUDY

2.1 Introduction

Today the construction industry is in need to find alternative techniques to reduce the consumption amount of cement by finding cost effective and environmental friendly materials (Bhat & Rao, 2014). One of the most attractive options is replacing cement partially with pozzolanic materials in order to reduce the amount of cement in concrete or mortar production, especially with waste materials (Shi & Zheng, 2007).

2.2 Pozzolanic Materials Used as a Cement Replacement

Standards defined pozzolanic materials as a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value, but, will in finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Materials having enough pozzolanic reactivity in a special physical and environmental status that can be used as a cement replacement material are called pozzolanic materials. These pozzolanic materials can improve both fresh (workability) and hardened (durability) properties of concrete (Siddique, 2007). Some of widely used and well known pozzolanic materials are briefly described below:

Fly ash: is the most popular pozzolanic material which is used in concrete production, either as a partial cement replacement or as an additive material. Fly ash is a by-product material which can be produced by burning of pulverized coal in thermal power plants. Typically, it has spherical shape particles and its diameter ranges from<1 μm to 150 μm. In addition, more than 85% of fly ashes formed from the elements such as silicon, aluminum, iron, calcium, and magnesium (Siddique, 2007; Yao, 2015). Using fly ash in concrete results in:

1) Fresh concrete: Improves finishing, increases workability and pumpability, and reduces bleeding and segregation.

2) Hardened concrete: Increases strength and durability, decreases permeability and reduces alkali silica reactivity and heat of hydration.

Ground granulated blast-furnace slag (GGBS): is a well-known pozzolanic material which is used in concrete or/and mortar matrix production, either partial cement replacement or additive. This material is produced as a by-product of the manufacturing of iron. GGBS mainly consists of CaO, SiO_2, Al_2O_3, MgO. It has the same main chemical compositions as ordinary Portland cement, but in different proportions (Siddique, 2007). Using GGBS as a cement replacement in concrete mixes results in:

1) Fresh concrete: Improves workability, pumpability and compaction characteristics of concrete placement.

2) Hardened concrete: Increases strength and durability, and reduces permeability. And also, makes concrete high resistance to chloride penetration, sulfate attack and ASR.

Silica fume (SF): is the ultrafine non-crystalline silica, produced in electric-arc furnaces as an industrial byproduct of the production of silicon metals and ferrosilicon alloys. Silica fume is extremely fine with particles size less than 1 μm in diameter and with an average diameter of about 0.1 μm and it is about 100 times smaller than average cement particles. Silica fume is typically used in amounts between 5% and 10% by mass of the total cementitious materials. It is used in applications, where a high degree of impermeability is needed and also in high-strength concrete (Kosmatka et al, 2002). Using Silica fume as a cement replacement in concrete mixes results in higher strength and durability and also, lower permeability (Sanjuan et all, 2015).

Waste glass powder: Glass is a formless material with high silica (SiO_2) content about 70%. When waste glass grounded to very fine powder (less than 600 micron) reacts as pozzolanic material with alkali in cement and cementations product, which improves mechanical properties of fresh and hardened concrete (Bhat, 2014). The aim of this study is considering "effects of glass powder as a partial cement replacement on mechanical properties and behavior of concrete".

Based on chemical compositions, glasses can be classified into many categories. The most widely used is Soda-lime glass, which is used in manufacturing containers, float sheets and bottles. According to chemical compositions, soda-lime glasses can be pozzolanic-cementitious materials (Shi & Zheng, 2007). Table 1 shows the typical chemical compositions of soda-lime glass.

Table 1: Typical Chemical Composition of soda lime glass (McLellan & Shand, 1984; cited in Shi & Zheng, 2007)

Chemical Composition		% by mass
Silicon dioxide	SiO_2	66–75
Sodium oxide	Na_2O	12–16
Calcium oxide	CaO	6–12
Aluminum oxide	Al_2O_3	0.7–7
Magnesium oxide	MgO	0.1–5
Potassium oxide	K_2O	0.1–3

In addition, Shi & Zheng (2007) stated, the use of waste glasses either as a cement or as an aggregate replacement in Portland cement concrete were concerned a lot of interests worldwide, due to the environmental and economic benefits. Moreover, ground glass powders can be used as cement replacement material, as a result of high pozzolanic reactivity, when its fineness increases.

Glass powder at elevated temperatures has a higher reaction and pozzolanic behavior. In contrast, it has no pozzolanic behavior at very low temperatures, 10 ℃. Also, it was found that glass cullet has considerable pozzolanic behavior for maximum size 0–25 μm, even at early ages, especially at high curing temperature, 50 ℃. Furthermore, calcium hydroxide content is noticeably reduced after seven days, which results in higher pozzolanicity (Mirzahosseini & Riding, 2015).

2.3 Workability of Concrete

As it’s known water is one of the main components in concrete mixes. In concrete mixes, water with Portland cement and cementitious materials form cement paste, which is accounting as an active part in concrete that binds the components together. In another words, water causes the hardening of concrete through hydration, which is a chemical reaction between water and cement to produce cementitious hydration

(Kosmatka, Kerkhoff & Panarese, 2011). As Gambhir (1995) argued, a part of mixing water is utilized in cement hydration to form binding matrix, the remaining water is served as a lubricant between fine and coarse aggregates and makes concrete workable.

2.3.1 Factors Influencing Workability of Concrete

Workability of concrete can be affected by many factors such as primarily component materials (water, cement, fine and coarse aggregates and admixtures), mix proportion and environmental climatic conditions (Gambhir, 1995). The followings are the list of factors influencing on workability of fresh concrete:

Water, cement and aggregate contents, aggregate properties (size, shape, surface texture and grading), using admixtures and supplementary cementitious materials and environmental and climatic conditions

Water has a great influence on the characteristics of concrete mixes physically and mechanically. Workability is one of the main physical appearances that can be affected by water quantity in concrete mixes. For example, high workable concrete can be obtained from high water binder ratio. Furthermore, workability covers a wide range of properties such as mobility, compatibility, Finish-ability and pump-ability of fresh concrete (Anderson & Dewar, 2003).

2.4 Compressive Strength of Concrete

Compressive strength is a maximum resistance of a concrete specimen to axial loading, which is horizontally applied by the special machine. It is generally expressed in Kilo-newton per millimeter square, which is denoted megapascal (MPa) or pounds per inch square (psi), mostly done at age of 28 days (Kosmatka et al, 2002). The following sub-section is explained the significance of studying compressive strength test in concrete.

Furthermore, general information on the effects of independent variables such as quantity of glass powder and w/b ratio are collected from previous studies.

2.4.1 Significance of Studying Compressive Strength in Concrete

As it is mentioned above, compressive strength of concrete is the most important mechanical properties, which is defined as a maximum (stress) load that can carry by a specific unit area. In some researches and books, the compressive strength was informed as an important mechanical property of concrete. In another words, in the construction industry for the purpose of quality control and specification the compressive strength is commonly used (Gambhir, 1995; Neville, 1987). The importance of compressive strength of concrete has encouraged researchers to focus on and deal with it more than any other mechanical properties, especially, when the studies were about the investigation of new materials in concrete, such as silica fume, Ground granulated blast-furnace slag, fly ash, glass powder and etc. (Siddique, 2007; Vijayakumar et al. 2013).

2.5 Modulus of Elasticity of Concrete

Modulus of elasticity (E) is one of the important mechanical property of concrete. It is known as reflecting the capability of concrete to deform elasticity. In other words, modulus of elasticity can be defined as the slope of the stress-strain relation curve up to 40% of ultimate compressive strength. With the higher elastic modulus, the material shows the more resistant to deform (Tia et al. 2005).

This section focused on the significant factors influenced modulus of elasticity and discussed the effects of cement replacement materials or pozzolanic materials on the modulus of elasticity of concrete specimens.

2.5.1 Factors Influencing Modulus of Elasticity of Concrete

Generally, there are unique relationships between strength and modulus of elasticity, hence any parameter affected on concrete strength, can affect the modulus of elasticity as well (Neville, 1987).

Followings are some affecting factors which are studied and investigated by scholars in concrete science and concrete materials field.

Effects of Coarse Aggregate Properties on Elastic Modulus: As it is clear, coarse aggregate is the main component of concrete. So, any variation in coarse aggregate types or coarse aggregate content will result in the change of elastic modulus of concrete (Tia et al. 2005)**.**

In term of coarse aggregate type, it is found that, different types of course aggregates can substantially influence on the elastic modulus of concrete (Zhou et al., 1995 & Shideler, 1957, as cited in Tia et al., 2005).

In the term of aggregate content, Neville (1987) indicated that, for given strength concrete, normal weight aggregate has a higher elastic modulus than hydrated cement paste. Concretes with higher aggregate content result in a higher modulus of elasticity.

Effects of Mix Design on Elastic Modulus: Normally, in the mix design of a concrete, only compressive strength of concrete is to be considered. The elastic modulus of concrete is mostly predicted by the equation recommended standards.

2.6 Splitting Tensile Strength of Concrete

Tensile strength is one of the important and basic mechanical properties of concrete. It is the maximum amount of tensile stress (load) that it can be subjected to concrete before failure. As it is known, concrete is very weak in tension compared to compression, due to its brittle nature. When the concrete is subjected to tensile forces cracks will develop. Thus, it is necessary to determine the load at which the concrete members may crack. Splitting tensile strength test is one of the methods to determine the tensile strength of concrete that it is known as indirect tensile strength, and mostly is greater than direct tensile strength.

According to ASTM standard C496/C496M – 11, splitting tensile strength test can be determined by "applying a diametral compressive force along the length of a cylindrical concrete specimen at a rate that is within a prescribed range until failure occurs" (p.1). 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.

The following subsection is explained the significance of studying tensile strength of concrete. Moreover, general information on the effects of independent variables such as quantity of glass powder and w/b ratio are collected from previous studies.

2.6.1 Factors Affecting Splitting Tensile Strength

As it is known, splitting tensile strength is a test to determine tensile strength of concrete. Therefore, any factors affecting strength of concrete, affects splitting tensile strength as well. In the following sections, several factors that affect the results of splitting tensile strength test are discussed.

Effect of Component Materials: it is well known that component materials of concrete such as cement, water and aggregates in both quality and quantity are controlling the strength of specimens.

Effect of Specimen (Dimensions) Length and Diameter: Length of cylindrical specimens does not seem to affect the test results of a given diameter, other than possible reducing variability for longer specimens. However, diameter of specimens has an effect on splitting test result. For Example, cylinders having a diameter of 100-mm were observed to have splitting tensile strengths about 10 % higher than 150-mm diameters (Wright, 1955; Melis et al. 1985, as cited in Lamond, 2006).

Effect of Bearing Strips: According to ASTM C496/C496M – 11, two bearing strips of 3.0 mm thick plywood, approximately 25 mm wide, and at least as long as the specimen shall be provided for the test. This bearing strips were use in order to conform the specimen surface and distribute the applying load from. Increasing the thickness of strips or using steel or any other stiff materials bearing strips may cause reduction in strength, due to their inability to conform to the specimen surface (Lamond, 2006).

Effect of Loading Rate: As with testing specimens for compressive strength and flexural strength, higher results are obtained for splitting tensile strengths, when the specimens are loaded at a more rapid rate (Zhang et al. 2016; Lamond, 2006).

2.7 Stress-Strain Curve

Stress-strain curve is a relationship between stress and strain of concrete, when it is subjected to the continuous loading under the control of strain or control of stress.

According to Watanabe et al. (2004), the significant factors for stress-strain curves in compressive is the localization of failure.

2.7.1 Factors Affecting Stress-Strain Relation

The factors influencing stress-strain relation are mentioned as water-cement ratio, aggregate to cement ratio and aggregate grading, curing conditions, specimen length, and examine loading rate (Komlos, 1969).

As reported by Carreira and Chu (1985), the following conditions strongly affected the shape of the uniaxial stress-strain diagram. First, testing conditions include stiffness of the testing machine, size and shape of the specimen, strain rate, and type of loading (preloading, cycling, etc.). Second, concrete characteristics include: water-cement ratio, cement content and characteristics, concrete unit weight, aggregate content and characteristics. Third, curing conditions and specimen age, when tested.

Lots of studies reported that the property of interfacial transition zone (ITZ) is responsible for the concrete properties (such as Failure behavior of concrete) under uniaxial loading (Tasong et al, 1999; Akçaoğlu et al, 2004; Xiao et al, 2013).

Xiao et al (2013) revealed that, in recycled aggregate concrete, the mechanical properties of new mortar matrix and relative mechanical properties between ITZs and mortar matrices play a significant role in the overall stress–strain relationship and failure patterns.

2.8 Water Absorption Capacity

Water absorption is a percentage increase in weight of oven dry concrete specimens after immersing in water for specified amount of time (ASTM C642 − 13). It is one of the significant properties of a good quality concrete, because surface water absorption of concrete can be useful to predict some properties of concrete, including permeability, compressive strength and resistance to sulfate attack as a durability test (Zhang & Zong, 2014).

Parrott (1992) stated that, water absorption is particularly relevant to durability of concrete in freeze-thaw damage, alkali-aggregate expansion, sulfate attack, chloride ingress and corrosion in reinforcement.

2.8.1 Factors Affecting Water Absorption Capacity

Water absorption of concrete can be affected by many factors such as primarily component materials (water, cement, fine aggregates, coarse aggregates and admixtures), mix proportion and environmental climatic conditions. Water absorption can be affected by water cement ratio, relative humidity and volume of aggregate (Castro et al, 2011).

Cement type is one of the significant factors effecting on water absorption capacity. Mors and Jonkers (2017) report that, using cement containing a high range slag content as clinker replacement (CEM III/B) increased the surface water absorption and to solve this problem they suggested adding healing agent to concrete.

Chapter 3

LITERATURE REVIEW

3.1 Introduction

The most used construction material all over the world is concrete. It is twice as much around the world than overall other materials, including steel, wood, aluminum and plastics. The most active and important component of concrete is cement. As Neville (1987) mentioned, the properties and performance of concrete determined by the properties of the cement. Furthermore, Pade (2007) reported, cement as the most significant material in concrete matrix which is a very comprehensive energy process and heavily polluting participant. In another study, researchers, Scrivener and Kirkpatrick (2008) cited that, cement industry produces 5% to 8% of the atmospheric CO_2 in the world which is largely responsible for the increase in greenhouse gas effects, contributes significantly to climate change.

Many researchers were contributed to find a waste material having pozzolanic behavior to replace cement such as waste glass, rice husk, blast furnace slag-the ultimate binder, ... etc. (Anwar et all, 2000; Talling & Krivenko, 1997; Federico & Chidiac, 2009).

3.2 Effect of Waste Glass Powder on Workability of Concrete

Cement is one of the factors influencing workability. Therefore, any change in cement quantity or quality affect workability of concrete. Replacing cement with pozzolanic materials is a kind of alteration in quantity and quality of cement that may have significant effect on concrete workability.

According to previous researches, when glass powder is used as a cement replacement material, two properties of glass powder greatly effects the workability of concrete mixes; the first one is the percentage of replacement, the second one is the fineness for same type of glass powder. Islam et al (2016) reported that, concrete workability increases with increasing cement replacement amount with glass powder. In this study 90 % passing (#200 sieve) GP replaced to cement up to 25% by unit weight. In another study, Bhat and Rao (2014) mentioned that, the quantity of water can be decreased with increasing the cement replacing up to 20% with glass powder of maximum size 600 micron in order to produce concrete with constant workability to obtain higher strength concrete.

Furthermore, Kumarappan (2013) stated that, slump of concrete increases as the glass powder in the mix increases up to 40% without mentioning glass powder size. But, Chikhalikar and Tande (2012) reported that, for GP passing through 600-micron sieve the workability of concrete increases with increasing cement replacement up to 20%, above this amount workability starts to decrease up to 40%. Similarly, Saribiyik et al (2013) reported in their studies that, workability in terms of slump test value increases as a result of increased glass powder proportion

3.3 Effect of Waste Glass Powder on Compressive Strength of Concrete

As it is known concrete is very sensitive structural material, any change in its component materials has effect on all concrete properties, especially when these changes are in its active part of concrete (water or cement). Compressive strength is one of these properties that is easily effected by such changes. One of these changes is cement replacing partially with other pozzolanic material such as fly ash, Silica fume, glass powder, etc. This part deals with glass powder as partial cement replacement and its effects on the compressive strength of concrete according to previous studies.

Many researches showed the possibility of using glass powder as a partial replacement of cement material in concrete mixes especially in terms of compressive strength. Vijayakumar et al (2013) reported in their study, when cement was replaced with glass powder by 20%, 30% and 40% by weight the compressive strength increased by 19.6%, 25.3% and 33.7% respectively, it means that cement can replace with glass powder up to 40% without any adverse effect, vice versa, it has great positive effect on compressive strength.

Kumarappan (2013) reported in his study, using GP can reduce the use of cement which is influence air pollution and CO2 emission, by replacing 10% cement content with GGP under normal curing temperature condition and for 0.5 water binder ratio, the compressive strength of concrete obtained higher than that of the control. Above 20% glass powder the strength substantially decreases.

3.4 Effect of w/b Ratio on Compressive Strength of Concrete

Most books and articles which is written about concrete science mentioned and described the effect of water binder or water cement ratio on the mechanical properties especially on the compressive strength of the concrete. For Example, the term “The lower the W/C, the higher the strength for similar other materials” is sited in different expressions in many references such as (Gambhir, 1995; Neville, 1987; Kosmatka, Kerkhoff & Panarese, 2011), but the above expression is right up to the amount that need for complete hydration whole cement content. Larrard (1999) demonstrate, for completing hydration of 1 gram of cement 0.24 gram of water is needed, that means w/b ratio cannot be less than 0.24. And also, Gambhir (1995) argued, a cement of average composition for chemical reaction requires about 25% of water by mass of the cement. In addition, an amount of water to fill gel pores.

Behnood (2008) reported that, the higher content of binder and lower water cement ratio (*w*/*c*) are the most important required parameters to produce HSC. Therefore, in order to achieve the required workability in lowest water content high-range water-reducing admixtures are used.

Haranki (2009) explored, strongest concretes in compressive strength can be produced with low water cement ratio, in contrast, higher water cement ratios will relatively produce weaker concretes.

3.5 Influence of Replacement and/or Additives on Modulus of Elasticity of Concrete

As it was mentioned above, modulus of elasticity (E) of concrete is greatly influenced by strength of concrete. Any changes in concrete components which affected strength may affect E as well,

In concretes, produced with Portland-natural pozzolana cement, early ages strength and E slightly decreased compared to concretes without pozzolans. However, the E of concretes containing highly reactive natural pozzolans at longer ages may be similar or slightly higher (Ramazanipur, 2014)

In concretes containing fly ash: Siddique (2007) argued, using fly ash addition as cement replacement material affects modulus of elasticity of concrete, it is almost the same as on compressive strength. Generally, in fly ash concretes the modulus of elasticity is lower at early ages and it is slightly higher at late ages.

Ramazanipur (2014) stated that, fly ash has little influence on the elastic properties of concrete compared to compressive strength. Furthermore, at early age the modulus of elasticity, like compressive strength is lower, at ultimate strength is higher when compared with concrete without fly ash.

3.6 Influence of Waste Glass Powder on Tensile Strength of Concrete

Vardhan et all (2015) stated that, splitting tensile strength of concrete specimens increases as the cement replacement percentage with glass powder increases, and becomes optimum at about 20% cement replacing and later decrease.

Subramani and Ram (2015) stated that, there was marginal improvement in the splitting tensile strength and considerable improvement in the flexural strength. Also, they concluded that 10% replacement of cement by glass powder is the best proportion.

3.7 Influence of Waste Glass Powder on the Stress-Strain Relation of Concrete

It is known that failure of concrete under loading associated with cracking; so, understanding the cracks formation, cracks propagation and factors influencing cracking are very important in concrete technology. It is observed that even before application of load, concrete has some defects either in pore or crack form. These cracks mostly exist between interface of cement paste and coarse aggregate (ITZ). The ITZ plays a significant role in the overall mechanical properties especially on failure patterns in stress–strain relationship (Xiao et al. 2013). Therefore, we can say that cement and all other materials in concrete mixes, may have a significant role in the stress-strain relationship.

Tasdemir et al (1998) observed that, in concretes with silica fume, the ITZ becomes more homogeneous and stronger and less stress induced microcracking occurs at the interface, and hence the cracks usually pass through the aggregates. However, in concretes without silica fume the cracks usually develop at the weak interface in the result of profusion of calcium hydroxide at the cement-aggregate interface and less dense calcium silicate hydrate around the coarse aggregate.

3.8 Influence of Waste Glass Powder on Water Absorption Capacity

According to previous articles replacing cement with pozzolanic materials such as fly ash, silica fume and ground granulated blast affected the total void ratios of concrete specimens, which is realtered to water absorption (Pitroda et al. 2013; Zhao et al. 2015).

Taha and Nounu (2008) reported that, using crashed glass in concrete has effect on reducing total amount of water absorption and restricting the migration of moisture and ions inside the concrete in the result of stopping the continuity of the pores and microcracks.

Using glass powder as a cement replacement material like all other mechanical properties of concrete may have an effect on water absorption capacity. Bhat and Rao (2014) reported that, the percentage of water absorption decreased with increased broken glass content. And also, they mentioned that concrete mixes with 20% broken glass powder had the lowest value of water absorption.

Chapter 4

RESEARCH METHODOLOGY

4.1 Introduction

According to the objectives of this thesis, fifteen different mixes were produced by replacing five different percentages (0%, 10%, 20%, 30% and 40%) of Waste glass powder (GP) for each of the three different w/b ratios (0.4, 0.5 and 0.6). The main goal was to determine the effects of GP incorporated with w/b on mechanical behavior and properties of concrete. For this purpose, the following experiments has been performed:

1- Slump test
2- Compressive strength test
3- Split tensile strength test
4- Modulus of elasticity test
5- Stress-Strain test
6- Water absorption capacity test

This chapter, covers the description of the materials used in the above listed experiments and also, explains the ASTM standard codes or any other standards that used in experimentation and the procedures of using machines, tools and test techniques in detail.

4.2 Materials Used

The materials which were used in the experimentations of this study are defined in the following sections:

4.2.1 Cement

CEM II Slag Portland cement of 42.5 grade is used in this research. This type is modified to resist a moderate sulfate attack. It usually generates less heat and slow rate of hydration.

4.2.2 Mixing Water

Drinkable tap water which is free from acids, alkalis, oils and organic materials was used for all concrete mixtures and curing process.

4.2.3 Fine Aggregate

Machine crushed fine aggregate with maximum size of 5 mm in diameter which is called sand, was used in this study. To find out gradation based on ASTM standard, C136M-14 sieve analysis was performed and controlled by C33/C33M-16 of ASTM standard as shown in Figure 3.

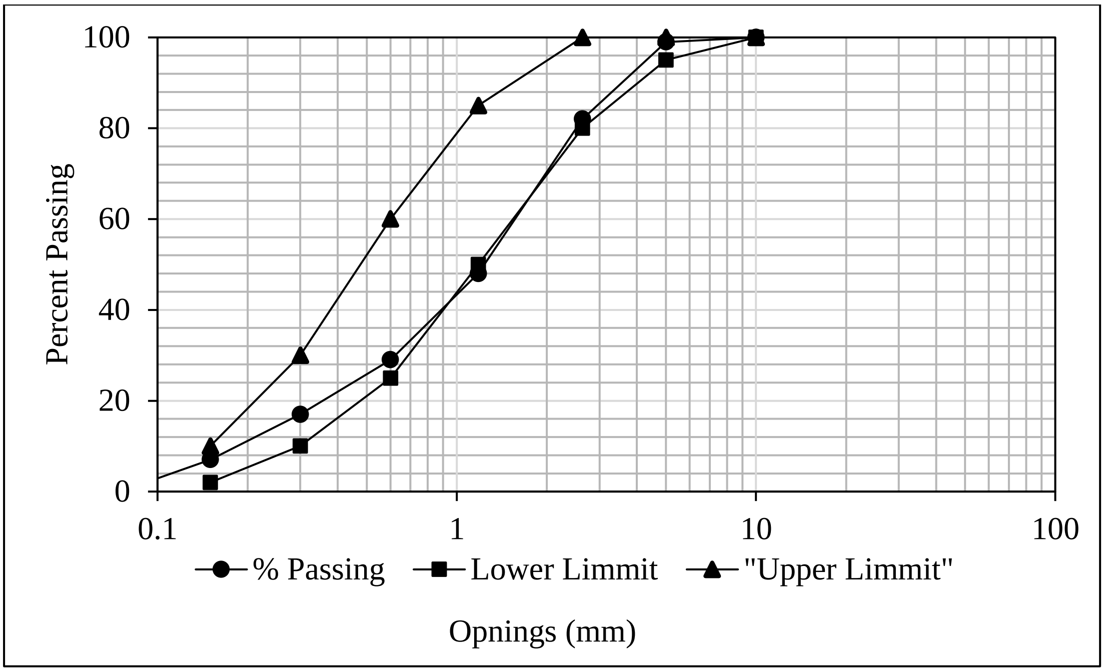

Figure 1: Sieve Analysis of Fine Aggregates

4.2.4 Coarse Aggregates

Machine crushed coarse aggregates were used in these experiments as gravel with three different sizes (10, 14, 20 mm in diameter). To find out gradation of coarse aggregates based on standard ASTM C136M-14 sieve analysis was performed and controlled by ASTM C33M-16 as shown in Figure 2.

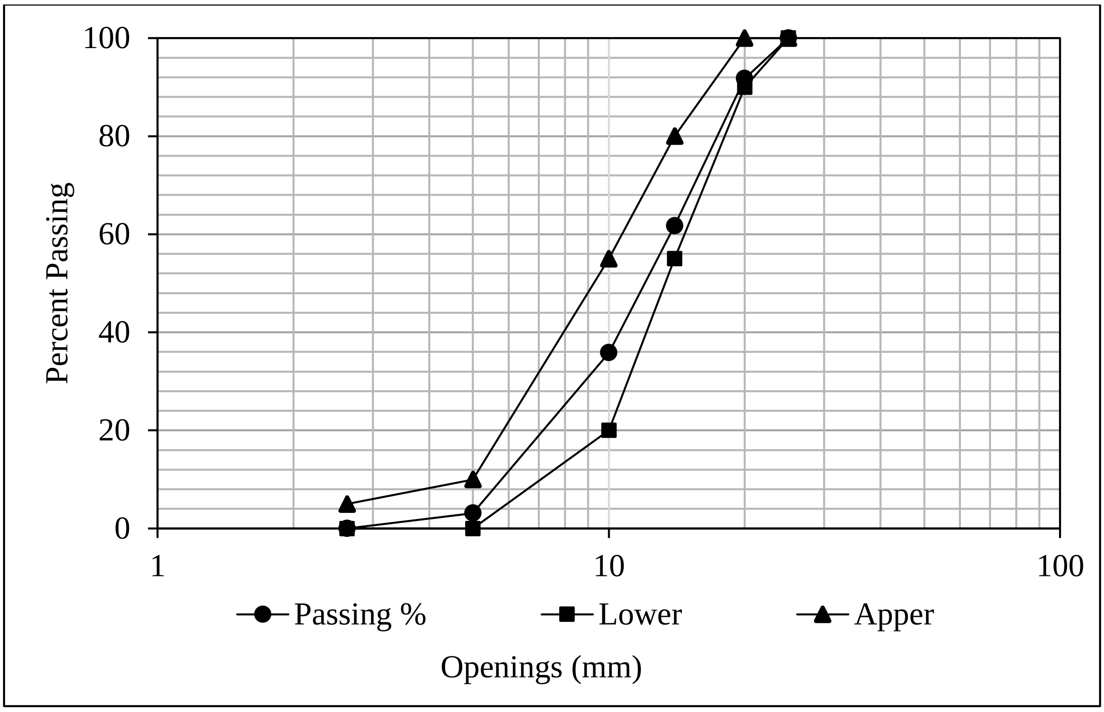

Figure 2: Sieve Analysis of Coarse Aggregates

4.2.5 Glass Powder

Waste glass powder less than 90 μm in diameter was used, which is produced from brown color bottles that mostly known as wine bottles. These bottles were collected from wine shops and beaches in Gazimağusa, North Cyprus. The collected bottles were washed and cleaned to remove paper labels and dust or any undesired materials. After drying, they were crushed manually by hummer and then they grinded with a rotary grinder machine.

Figure 3: Grinded Glass Powder – fineness ≤ 90 μm in diameter

4.2.6 Superplasticizer

Type F Polycarboxylic high range water-reducing admixture which is commonly known as Master GLENIUM 27 was used in this experimental work, for only 0.40 w/b mixes.

4.3 Mix Design

The simplest definition of mix design is calculation of the quantities and ratios of main component materials of concrete mixes for required characteristic strength, specific material properties and workability in order to get the best concrete mix. The mix designs illustrated in Tables 2, 3, and 4.

The mix design proportions for control groups with 0% cement replacement with GP were 1:2.33:3.07 for cement sand and gravel respectively.

Table 2: Quantities and proportions of mixing materials for 0.4 w/b ratio concrete mixes

Concrete Type	GP (%)	C (kg/m^3)	GP (kg/m^3)	W (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	SP. (kg/m^3)
Control	0	350	0	140	815	1075	4.90
GP10	10	315	35	140	815	1075	4.90
GP20	20	280	70	140	815	1075	4.90
GP30	30	245	105	140	815	1075	4.90
GP40	40	210	140	140	815	1075	4.90

GP: Waste Glass Powder; C: Cement; FA: Fine Aggregate; CA: Coarse Aggregate.

Table 3: Quantities and proportions of mixing materials for 0.5 w/b ratio concrete mixes

Concrete Type	GP (%)	C (kg/m^3)	GP (kg/m^3)	W (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	SP. (kg/m^3)
Control	0	350	0	175	815	1075	0
GP10	10	315	35	175	815	1075	0
GP20	20	280	70	175	815	1075	0
GP30	30	245	105	175	815	1075	0
GP40	40	210	140	175	815	1075	0

GP: Waste Glass Powder; C: Cement; FA: Fine Aggregate; CA: Coarse Aggregate.

Table 4: Quantities and proportions of mixing materials for 0.6 w/b ratio concrete mixes

Concrete Type	GP (%)	C (kg/m^3)	GP (kg/m^3)	W (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	SP. (kg/m^3)
Control	0	350	0	210	815	1075	0
GP10	10	315	35	210	815	1075	0
GP20	20	280	70	210	815	1075	0
GP30	30	245	105	210	815	1075	0
GP40	40	210	140	210	815	1075	0

GP: Waste Glass Powder; C: Cement; FA: Fine Aggregate; CA: Coarse Aggregate.

4.4 Experimental Program

In order to test the effects of replacing cement with GP, five different percentages of GP (0%, 10%, 20%. 30% and 40%) with three different w/b (0.4, 0.5 and 0.6) were used. For this purpose, fifteen different batches were prepared for the required tests. In this study, the mechanism of the experiments is a comparison between each percentage of replacing cement with GP to the control group specimens, in which 0% cement were replaced with GP for each w/b. In addition, the results of different w/b ratios compared, in order to determine the greatest effect of GP in different w/b ratios on mechanical properties of concrete.

4.4.1 Concrete Mixing Procedure

All concrete mixtures were mixed with a 0.25 m^3 capacity mixer. The dry materials were added to the mixer according to the following order: half of coarse and fine aggregates and cement (or mixed cement with GP) was added, then another half of coarse and fine aggregates. They were mixed for about 45 seconds, then water (or mixed water and superplasticizer) was added. Finally, they mixed for 120 more seconds.

4.4.2 Fresh Concrete Tests, Workability

In order to determine the effects of five different percentages of GP (0%, 10%, 20%, 30% and 40%), as a cement replacement material on workability of fresh concrete with three different w/b ratios (0.4, 0.5 and 0.6), the slump test was applied (see Figure 4). The slump test was done according to ASTM C143/C143M 15a standard test method for measuring the workability of hydraulic-cement concrete.

Figure 4: Measurement of Slump Value – Slump Test

4.4.3 Specimen Preparation and Curing

In this experimental study, two different shapes and sizes of specimens were produced in order to examine the behaviors and properties of hardened concrete. These are six cylinders (with 100 mm diameter × 200 mm long) and three cubes (with 150 × 150 × 150 mm) were used for each concrete mix.

Before putting concrete to the molds, the molds were cleaned and oiled with thin layer of oil in order to prevent the chemical reaction between concrete and steel molds and easy demolding specimens.

After finishing slump test, immediately the concrete was mixed for 45 more seconds. After that, immediately the molds were filled completely, then they were put on vibration machine, in order to compact as it is shown in Figure 5. After that, the specimens were saved in the curing room with a relative humidity of 99%. Twenty-four hours later, the specimens were demolded.

Figure 5: Standard Compaction of Specimens

After demoulding, immediately the specimens were put to the curing water tank with normal temperature about 25 ℃, for 28 days until the day of testing, as it is shown in Figure 4.

Figure 6: Standard Curing of Specimens – Curing Tank

4.5 Testing for Hardened Concrete

In order to achieve the objectives of this study, the following experiments were performed to test hardened concrete specimens prepared in different shapes and sizes.

4.5.1 Stress-Strain Test

In order to be able to see the influence of GP on microcracking behavior of concrete, stress - strain diagrams were obtained by subjecting the cylinder specimens (100 mm diameter × 200 mm long) to compressive loading. The ultimate capacity of the universal compressive testing machine is 3000 kN. The specimens were tested with a constant loading rate of 0.03 kN/s.

Figure 7: Stress - Strain Diagram Test Details

4.5.2 Compressive Strength

To investigate the effects of replacing cement with GP for three deferent w/b ratios on the compressive strength, the cylindrical specimens with 100 mm diameter and 200 mm long were prepared and subjected to testing in 28 days age according to ASTM

C39/C39M – 17 standard specifications. The test was done on three specimens for each w/b ratios with different proportion of GP.

4.5.3 Modulus of Elasticity (E)

To measure the effects of replacing cement with GP on E, the cylinder specimens (100 mm diameter × 200 mm long) were prepared and tested regarding to specifications and procedures described in ASTM C469/C469M − 14. The test was done on three specimens for each w/b ratios with different proportion of GP.

4.5.4 Splitting Tensile Strength

To determine the effect of replacing cement with GP on tensile strength for different w/b ratios, the cylinder specimens (with 100 mm diameter × 200 mm long) were prepared and broken for age of 28 days. The test procedures were done according to ASTM C496/C496M – 11. The test was performed on three specimens for each w/b ratios with different proportion of GP.

Figure 8: Splitting Tensile Strength Test Apparatus

4.5.5 Water Absorption Capacity

To measure water absorption capacity of concrete specimens modified with five different percentages of GP for three deferent w/b ratio, the cube specimens (with150 × 150 × 150 mm in dimensions) were subjected to testing according to ASTM C642 – 13 standard specifications. Three specimens were tested for each glass powder proportion with different w/b ratios.

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter includes the test results and critical discussions of all performed experiments for fifteen different concrete mixes differing in quantities and proportions of ingredients. For analyzing experimental results, outcomes are tabulated in tables or drawn in graphs by using Microsoft Office, Excel 2016 program.

5.2 Analyses of Experimental Results

Discussions related to the experimental results were done effectively for further understanding; the causes of the outcomes depending on five different proportions of GP and three different w/b.

5.2.1 The Effects of Different GP Proportions and W/b Ratios on Workability

The slump test results of fresh concrete mixes for five different percentages of glass powder (0%, 10%, 20%, 30% and 40%) replacement to cement with three different w/b ratios (0.4, 0.5 and 0.6) were illustrated in Figure 9. As it is clear from the figure, GP has a great influence on the workability of fresh concrete for each w/b.

In concrete mixes with 0.40 w/b ratio, the workability was increased with increasing glass powder percentage up to 30%. After that, the workability started to decrease with 40% cement replacement with GP.

In concrete mixes with 0.50 and 0.6 w/b ratio, the workability was increased with increasing GP percentage up to 20%. Later, decrement in workability was observed up to 40% GP proportion. Optimum workability for 0.5 and 0.6 w/b mixes is obtained when GP replacement is 20%, while for low w/b (0.4 and 1.4 superplasticizer) mixes this value is 30%. However, the maximum importance should be given to the interesting outcome obtained for 0.5 w/b mixes. The slump values are very low in comparing with the other two w/b ratios (0.4 and 0.6).

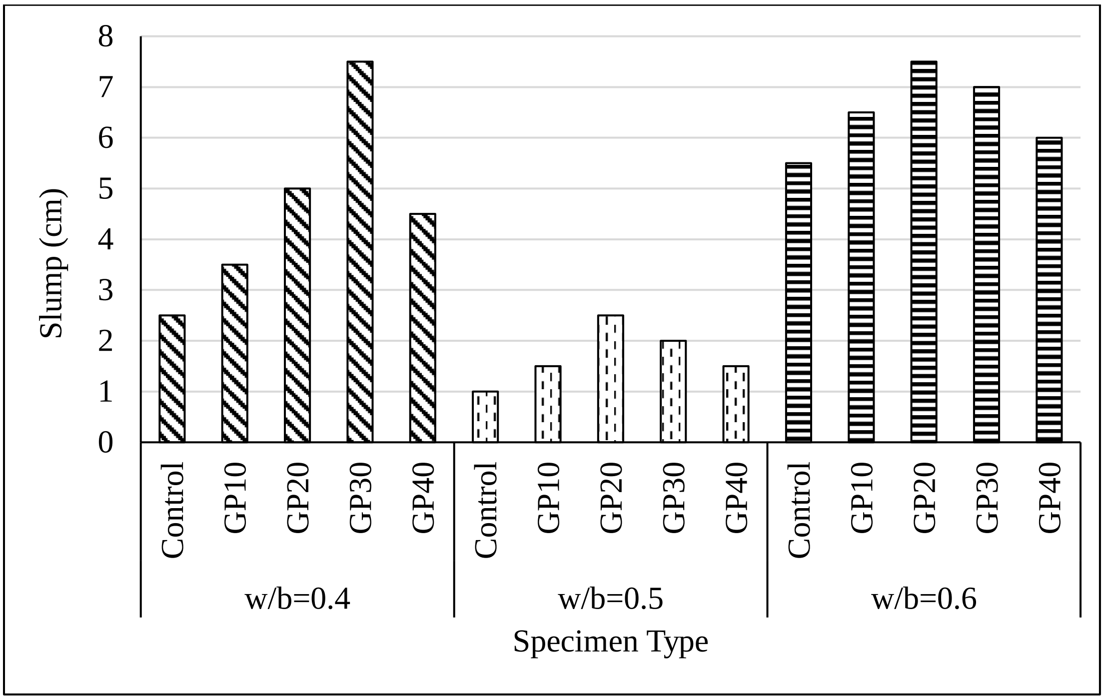

Figure 9: Effect of GP and w/b on Workability – Slump Flow

5.2.2 The Effects of Different GP Proportions and W/b Ratios on Microcracking Behavior of Concrete Under Compressive Loading

Stress-strain curves of fifteen different mixes were obtained by subjecting the specimen to compressive loading with a 0.03 mm /sec strain rate control. Test results belonging to three different w/b ratios are presented in figures 10, 11 and 12 respectively. The Ultimate compressive strength values of these specimens were within the range of 25 MPa to 55 MPa. Strain at peak stress mostly increased with increasing of compressive strength.

From figure 10, glass powder effect as a partial cement replacement on microcracking behavior of 0.6 w/b ratio concrete can be observed. The stress-strain curves became non-linear at a certain stress level. This non-linearity is due to the combination of microcracks at the paste-aggregate interface. The changes in slopes of stress-strain curves are categorized with proper tangent lines and therefore microcracking behavior is defined with four regions as it is tabulated in Table 5.

Table 5: Effect of GP on Microcracking Behavior of 0.6 w/b Concrete: By Following the Stress – Strain Curve Changes.

GP replacement to cement (%)	Stress Levels with respect to ultimate Compressive Strength (%)			
	First tangent line	Second tangent line	Third tangent line	Fourth tangent line
Control	35	68.5	84	92
10	46	71	85.5	93.5
20	50	67.5	81.5	95
30	53	76	88	99
40	39	64	82.5	95.5

Changes in the slopes of stress-strain curves showed that up to 30% GP replacement to cement resulted in higher stress levels for crack formation and propagation, when compared with control concrete. However, at 40% GP replacement case, all stress levels corresponding to different crack formation and propagation were lower.

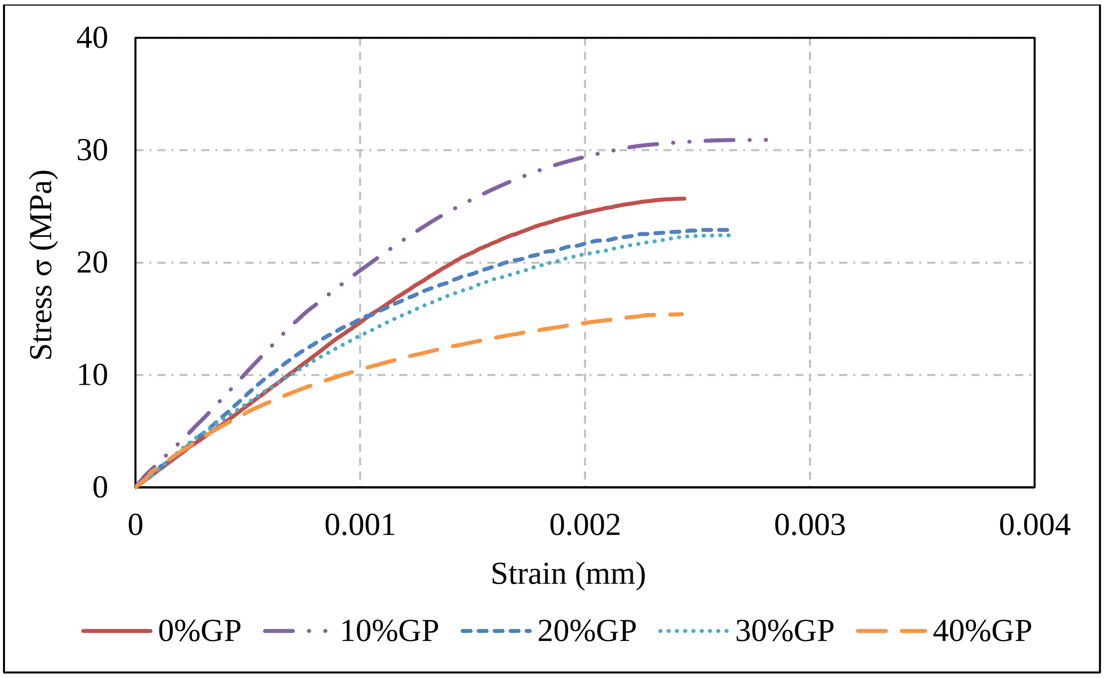

Figure 10: Effect of GP on Stress - Strain Relation for 0.6 w/b Concretes

From figure 11, glass powder effect as a partial cement replacement on microcracking behavior of 0.5 w/b ratio concrete can be observed. The stress-strain curves became non-linear at a certain stress level. This non-linearity is due to the combination of microcracks at the paste-aggregate interface. The changes in slopes of stress-strain curves are categorized with proper tangent lines and therefore microcracking behavior is defined with four regions as it is presented in Table 6.

Table 6: Effect of GP on Microcracking Behavior of 0.5 w/b Concrete: By Following the Stress – Strain Curve Changes

GP replacement to cement (%)	Stress Levels with respect to ultimate Compressive Strength (%)			
	First tangent line	Second tangent line	First tangent line	Fourth tangent line
Control	32	65	87	95
10	33	66	83	95
20	46	70	88	97
30	42	70	84	97
40	33	66	77	93.5

Changes in the slopes of stress-strain curves showed that up to 20% GP replacement to cement resulted in higher stress levels for crack formation and propagation, when compared with control concrete. However, at 40% GP replacement case, all stress levels corresponding to different crack formation and propagation were lower.

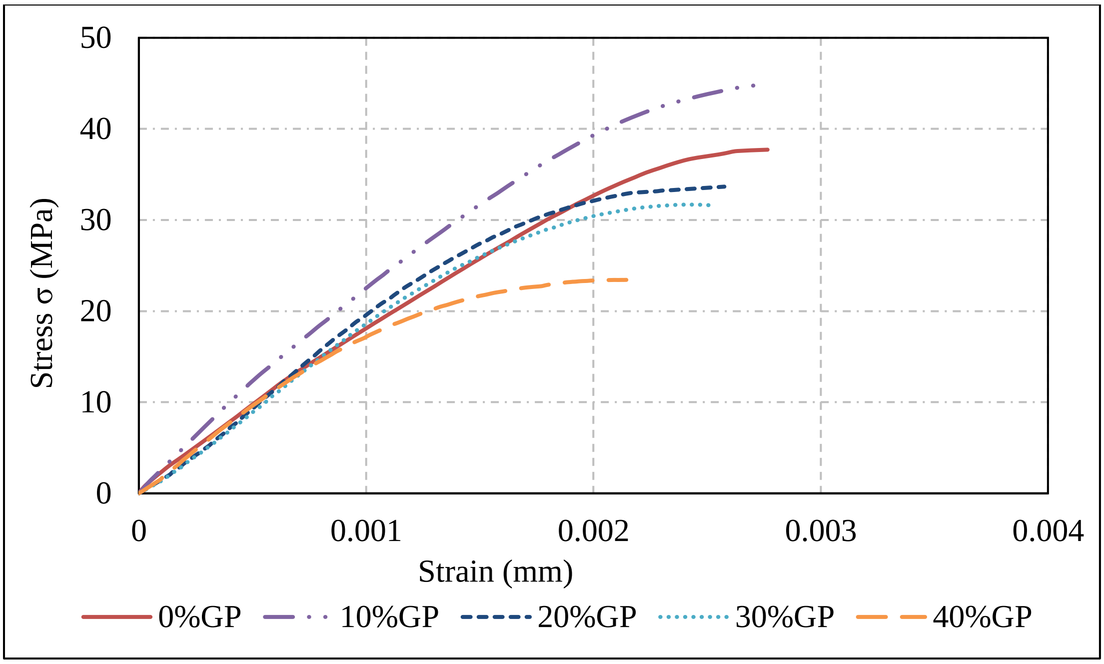

Figure 11: Effect of GP on Stress - Strain Relation for 0.5 w/b Concretes

From figure 12, glass powder effect as a partial cement replacement on microcracking behavior of 0.4 w/b and 1.4 superplasticizer ratio concrete can be observed. The stress-strain curves became non-linear at a certain stress level. This non-linearity is due to the combination of microcracks at the paste-aggregate interface. The changes in slopes of stress-strain curves are categorized with proper tangent lines and therefore microcracking behavior is defined with four regions as it is tabulated in Table 7.

Table 7: Effect of GP on Microcracking Behavior of 0.5 w/b Concrete: By Following the Stress – Strain Curve Changes

GP replacement to cement (%)	Stress Levels with respect to ultimate Compressive Strength (%)			
	First tangent line	Second tangent line	First tangent line	Fourth tangent line
control	48	75	89	98
10	51	75	90	98
20	52	78	90	98
30	48	73	89	98
40	44	76	89	97.5

Changes in the slopes of stress-strain curves showed that up to 20% GP replacement to cement resulted in higher stress levels for crack formation and propagation, when compared with control concrete. However, at 40% GP replacement case, all stress levels corresponding to different crack formation and propagation were lower.

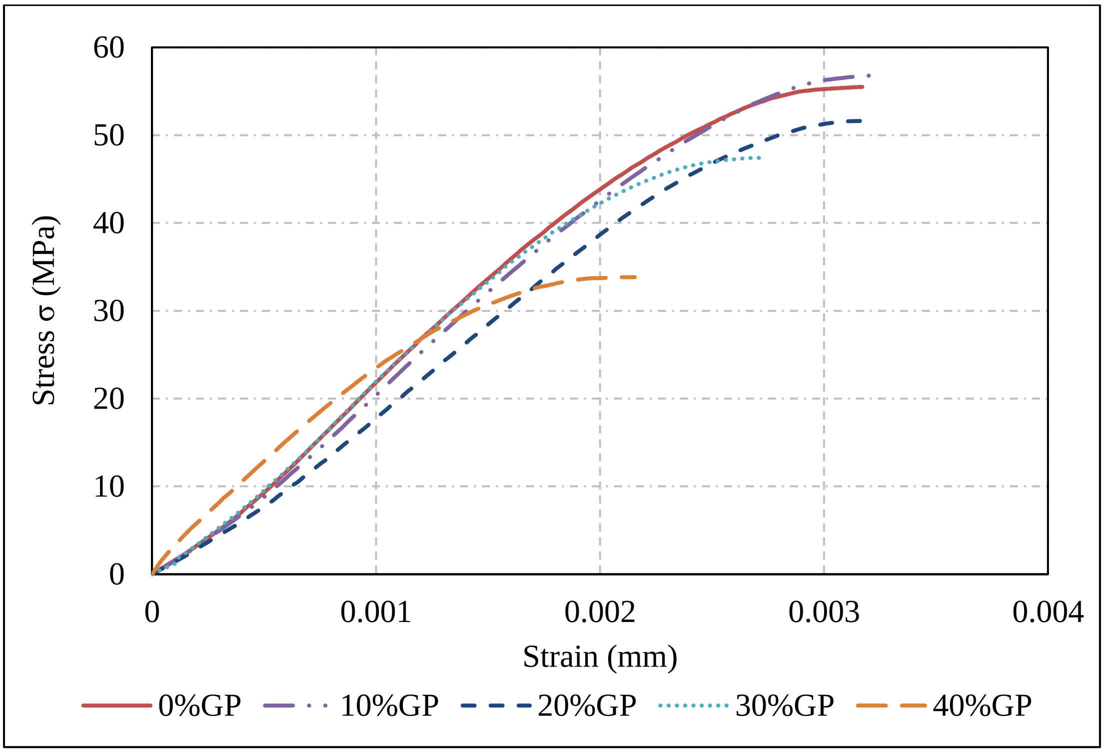

Figure 12: Effect of GP on Stress - Strain Relation for 0.4 w/b Concretes

5.2.3 The Effects of Different GP Proportions and W/b on Compressive Strength

The ultimate stress results from stress strain curves were taken as a compressive strength test results for all fifteen concrete mixes and are shown and evaluated in Figure 14. The individual compressive strength values are shown in Appendix D.

As it is clear from figure 13, the compressive strength developed for concrete mixes containing 10 % GP compared to control mixes without GP (0% GP) and it was the maximum achieved value for all used w/b ratios (0.6, 0.5 and 0.4). But, the increasing rate was different. For example, concrete with 0.6 w/b ratio was the most improved one and concrete with 0.4 w/b ratio was the lowest improved one. In concretes containing 20%, 30% and 40% GP the strength starts to decrease with increasing glass powder content, in which the lowest compressive strength achieved with 40% of cement replacement for all different w/b.

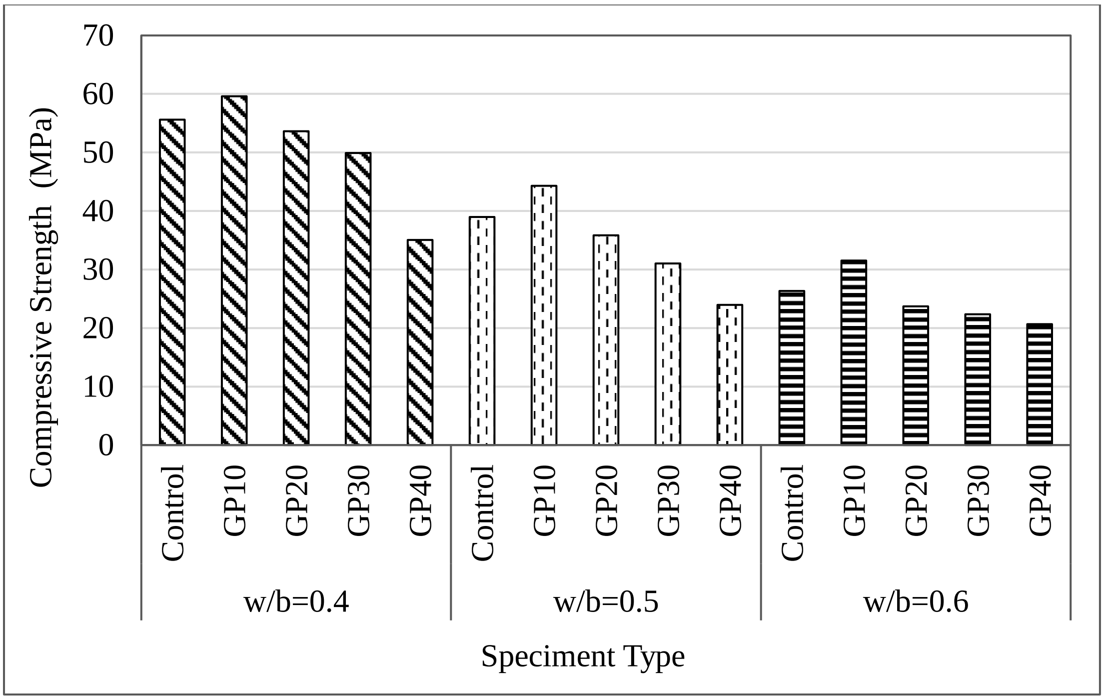

Figure 13: Effect of GP and w/b on on 28 – days Compressive Strength.

5.2.4 The Effects of Different GP Proportions and W/b Ratios on Tensile Strength

The average of three specimens for splitting tensile strength test results of fifteen concrete mixes of five different glass powder contents with three different w/b ratios are exposed in Figure 14. The individual results are shown in Appendix E.

In all three w/b ratios, the maximum value for splitting tensile strength achieved when 10% of cement replaced by glass powder and the most increased rate obtained in 0.4 w/b ratio concrete mixes. In 20% replacement of cement by GP compared to control specimens the splitting tensile strength increased, while in replacing 30% of cement, the splitting tensile started to decrease, except in concrete specimens with 0.5 w/b ratio, which was still greater than control specimens. Next to, the lowest splitting tensile strength achieved with 40% cement replacement for all different w/b ratios.

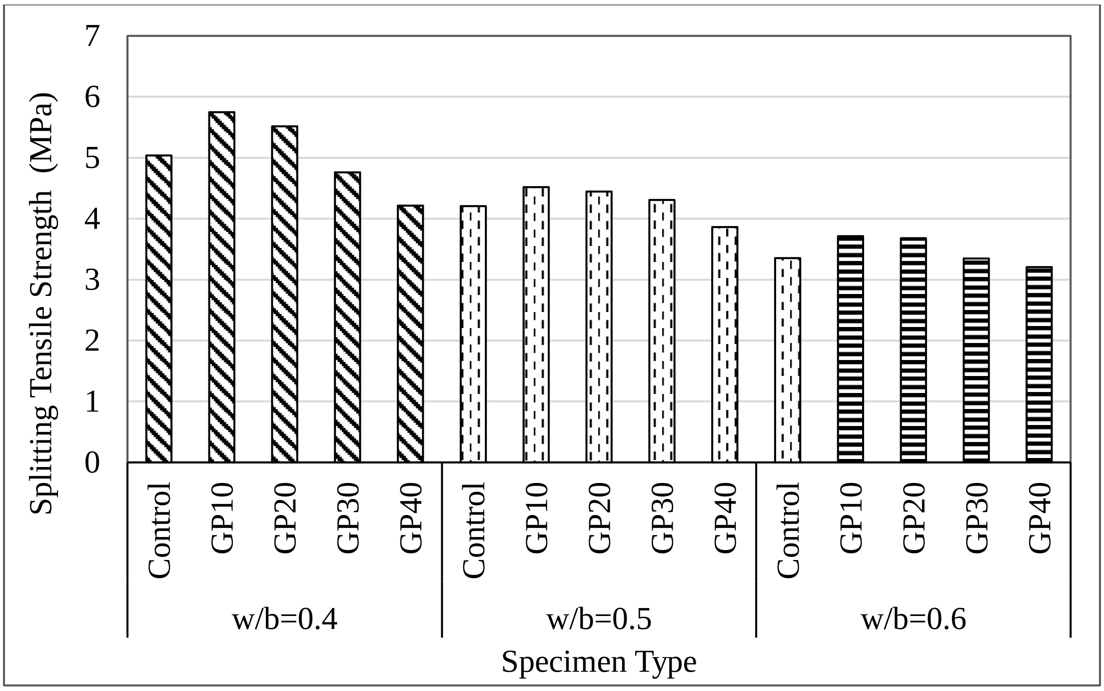

Figure 14: Effect of GP and w/b on 28 – days Splitting Tensile Strength

5.2.5 The Effects of Different GP Proportion and W/b Ratios on Modulus of Elasticity (E).

Figure 15, illustrated the average results of three specimens for modulus of elasticity test of fifteen concrete mixes for five different glass powder contents (0%, 10, %20, %30, % and 40%) with three different w/b ratios (0.4, 0.5 and 0.6).

As it is clear from Figure 15, the modulus of elasticity developed for all concrete mixes containing 10 % GP compared to control mixes containing 0% GP and it was the maximum achieved value in 0.4 and 0.6 used w/b ratios; but increasing rate was different. For example, concrete with 0.4 w/b ratio was the most improved and concrete with 0.5 w/b ratio was the lowest improved. In concretes containing 20% GP with 0.5 w/b ratio the maximum value was achieved, while in 0.4 and 0.6 w/b ratio concretes modulus of elasticity started to decrease. However, it was still greater than control mixes. Moreover, the lowest modulus of elasticity achieved with 40% of cement replacement for all different w/b ratios.

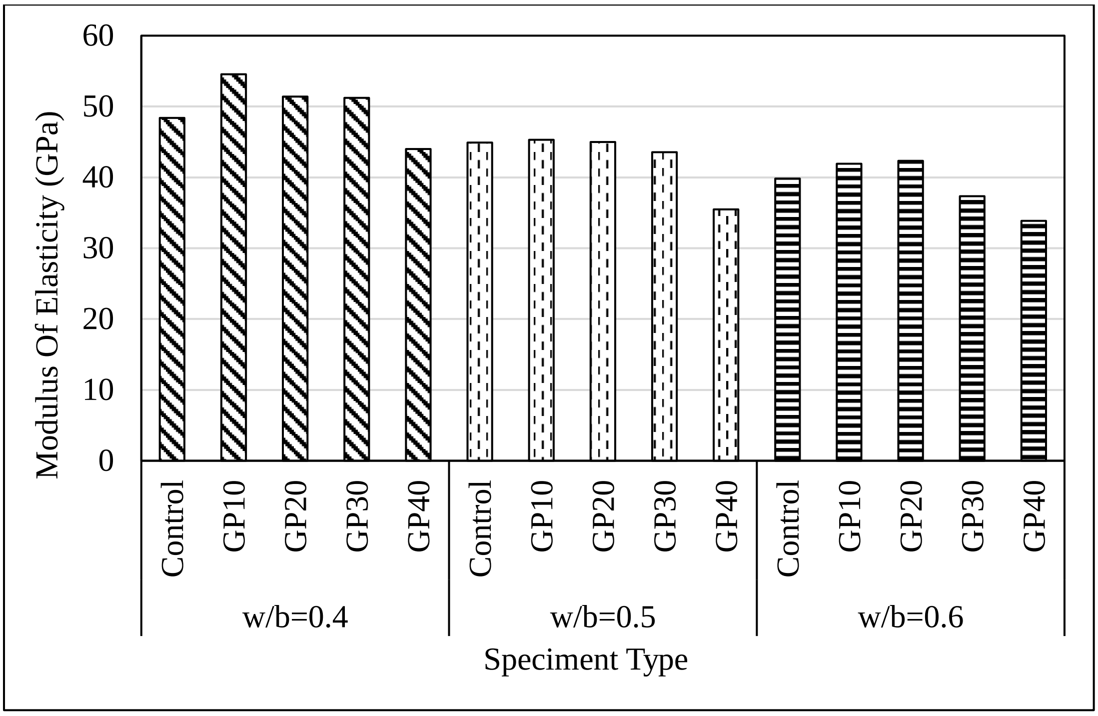

Figure 15: Effect of GP and w/b on 28 – days Modulus of Elasticity

5.2.6 The Effects of Different GP Proportions and W/b Ratio on Water Absorption Capacity

The water absorption capacity results of hardened specimens for five different percentages of GP (0%, 10%, 20%, 30% and 40%) replacement of cement with three different w/b ratios (0.4, 0.5 and 0.6) were illustrated in Figure 16.

As it is shown in the figure 16, GP has a great influence on the water absorption capacity, in which the water absorption capacity decreased for concrete mixes containing up to 20 % GP and it was the minimum value for both 0.6 and 0.4 w/b ratios. Nonetheless, there was an increase in water absorption capacity in concretes with more than 20% GP content. In concretes with 0.5 w/b ratio the water absorption capacity decreased up to 30% cement replacement, while, in 40% cerement replacement, water absorption capacity increased.

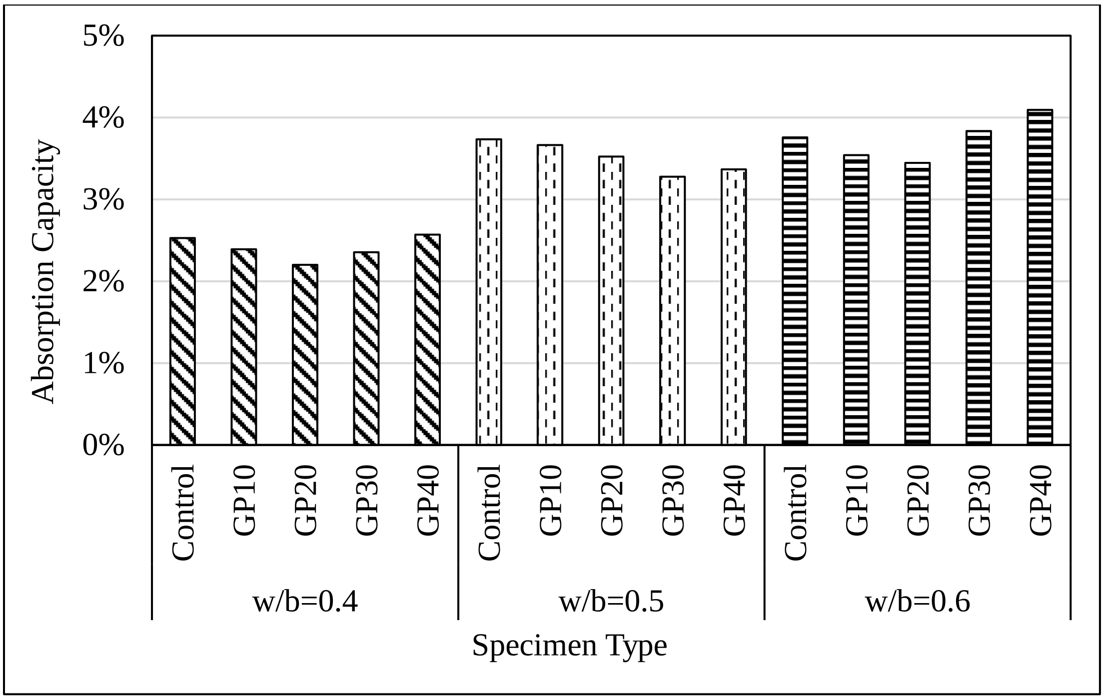

Figure 16: Effect of GP and w/b on Water Absorption Capacity

5.3 Discussions

This section deals with the causes of positive and negative effects of using glass powder as a partial cement replacement material for three deferent water binder ratios (0.6, 0.5 and 0.4 with 1.4% superplasticizer) and compares the results with the previous studies.

Slump Test (Workability): As a result of this study, GP could increase workability of concrete mixes up to 20% replacement, while using more 20% reversed the workability to decrease. In this line, Chikhalikar and Tande (2012) used GP passing through 600-micron sieve and the results revealed that the workability of concrete increased with the cement replacement increasing up to 20% and above this amount, the workability started to decrease up to 40%.

In this study, the increased rates of workability were as a result of:

1- Lower water consumed by GP particles for chemical reaction activities comparing to cement particles.

2- Water replaced by GP to fill the voides in concrete mixture, which increased free water content, thus increased the workability of concrete mixes. In another word, GP acted as a filler material in concrete and had possetive effectes, until concrete needed to fill the voides.

The decresed rates of workability resulted from the following points:

1- Cement is softer than GP. Indeed, higher amount of GP and lesser amount of cement content resulted in losing softness property of concrete.

2- Using GP more than this amount that was need to fill concrete voids caused agglomeration of GP particles, hence, increased pores and voids among collected glass particles.

Compressive Strength: Using GP as a partial cement replacement up to 10% increased the compressive strength of concrete, following that, the strength started to decrease. Similar to the current study, Kumarappan (2013), found that by replacing 10% cement content with ground glass powder under normal curing temperature condition, the compressive strength of concrete obtained higher than that of the control. Above 20% glass powder the strength substantially decreased.

In this study, the increased rates of compressive strength up to 10% GP content affected by the followings:

1- As a result of chemical reactions of cement particles, some amount of heat was produced, which could increase the chemical reaction activities (pozzolaninty) of GP particles.

2- Some amounts of glass powder acted as a filler material in concrete, which decreased the total voids in concrete.

In contrast, the below points caused a decrease in the compressive strength for more than 10% GP replacement:

1- By reducing cement amount in concrete mixes lesser heat was produced. Therefore, the produced heat was not sufficient to encourage the chemical reaction (pozzolaninty) of all GP particles.

2- Pores and voids increased as a result of agglomerated GP particles. In other words, less dense concrete was produced, which resulted in less compressive strength concrete.

Tensile Strength: GP increased the tensile strength of concrete in terms of splitting tensile strength up to 20%, following which the splitting tensile strength started to decrease. This result has been confirmed by the study of Vardhan et all (2015). These researchers stated that as the cement replacement percentage with GP increases, the splitting tensile strength of concrete specimens also increases and the results become optimum at about 20% cement replacing and later decrease.

Using GP up to 20% as a partial cement replacement material increased the splitting tensile strength of concrete, because:

1- Glass powder particles have angular shap, which made concrete more difficult to splitting.

2- Up to the before mentioned amount, the produced heat as a result of chemical reactions of cement particles still can encourage the chemical activity (pozzolaninty) of GP.

Using GP more than 20% as a partial cement replacement material caused decreasing the splitting tensile strength of concrete, because:

1- By reducing cement amount in concrete mixes lesser heat was produced. Therefore, the produced heat was not sufficient to encourage the chemical reaction (pozzolaninty) of all GP particles.

2- Pores and voids increased as a result of agglomerated GP particles. In other words, less dense concrete was produced, which resulted in less splitting tensile strength of concrete.

Elasticity: glass powder increased the elasticity of concrete in terms of modulus of elasticity and stress strain relationship up to specific amount, following which they started to decrease. According to Neville (2010), there are unique relations between strength and modulus of elasticity, hence any parameter which has effect on concrete strength, can affect modulus of elasticity. Indeed, in this study the same factors affected both compressive strength and elasticity for the same water-cement ratio and GP content.

Water Absorption Capacity: GP decreased the voids and capillaries inside concrete specimens up to 10% to 20%, resulted in reducing the water absorption capacity, following which water absorption capacity started to increase. Consistent with this finding, the results of a study by Bhat and Rao (2014) indicated that, as the cement replacement percentage with GP increases, the percentage of water absorption capacity of concrete specimens decreases. These researchers replaced cement by GP up to 20%.

These changes in the capacity of water absorption obtained, because some amount of GP particles acted as a filler material in concrete that decreased the total voids in concrete. However, using high amount of GP simultaneously led to decrease cement content and to agglomerate the glass particles, thus, the new pores and voids were made between GP particles.

Chapter 6

CONCLUSIONS

6.1 Conclusions

In this study, three different classes of concrete (C25, C35 & C55) were used with three different water binder ratios (0.6, 0.5 and 0.4+1.4% superplasticizer). For these concrete classes, five different percentages of replacing cement with glass powder (0%, 10%, 20%, 30% & 40%) were selected to be tested. The mixes with 0% cement replacement with glass powder or concretes without glass powder were used as a control. The results of the testing for fresh and hardened concretes led to draw the following conclusions and some suggestions for future researches, which are presented below.

- w/b had a moderate effect on concretes which modified with partially replacing cement by GP.

- Using GP as a partial cement replacement up to 20%, increased the workability of concrete for all different w/b. However, in cement replacement with GP up to 30%, only for concretes with 0.4 w/b and 1.4% superplasticizer the workability of concretes increased.

- GP showed both pozzolanic activity and filler behavior under normal curring temperature up to 10% and/or 20% cement replacement with GP.

- GP had some positive effects on stress-strain relationship; In general, these effects increased with increasing cement replacement percentage with GP and decreased with decreasing w/b ratio.

- Replacing of 10% cement with GP increased the compressive strength of concretes for all different w/b and the most effective w/b ratio was 0.6.

- Partial cement replacement with GP up to 20% improved the splitting tensile strength for all concrete with different w/b. However, in cement replacement with GP up to 30%, only for concretes with 0.5 the splitting tensile strength of concretes improved.

- Replacing cement with GP up to 20%, improved modulus of elastisity for all concretes with diffrent w/b. However, in cement replacement with GP up to 30%, only for concretes with 0.4 w/b and 1.4% superplasticizer the modulus of elasticity of concretes improved.

- Although replacing cement with GP up to 20% decreased water absorption capacity for all concretes with different w/b, in cement replacement with GP up to 30%, only for concretes with 0.5 w/b water absorption capacity decreased.

- Overall, replacing 10% cement with GP positively affected all the tested physical and mechanical properties of concrete. On the other hand, negative effects obtained when 40% cement was replaced by GP.

6.2 Recommendation for Future Studies

For future studies, it is recommended that researchers focus on:

1- Using more accurate percentags of glass powder as a cement replacement material in order to determine the exact ultimate replacement percentage acording to each mechanical properties.

2- Studying the effects of glass powder as a cement replacement material on the steel reinforced concrete in order to determine the posibility of using glass powder in offshore structures.

3- Studying the effects of combination of glass powder with other pozzolanic material as a partial cement replacement on the properties and behaviores of different tyepes concrete.

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APPENDICES

Appendix A: Mix-Design Form

Table 1 Concrete mix design form

Job title [redacted]

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	25 N/mm^2 at 28 days; Proportion defective .... %
	1.2	Standard deviation	Fig 3	8 N/mm^2 or no data .... N/mm^2
	1.3	Margin	C1 or Specified	(k = ...) 1.28 × 8 = ~~10.24~~ 11.0 N/mm^2; .... N/mm^2
	1.4	Target mean strength	C2	11 + 25 = 36 N/mm^2
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.6 } Use the lower value: 0.6
	1.8	*Maximum free-water/ cement ratio*	*Specified*	X
2	2.1	Slump or Vebe time	Specified	Slump 50 mm or Vebe time .... s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	210 → 210 kg/m^3
3	3.1	Cement content	C3	210 ÷ 0.6 = 350 kg/m^3
	3.2	*Maximum cement content*	*Specified*	X kg/m^3
	3.3	*Minimum cement content*	*Specified*	X kg/m^3
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 → 350 kg/m^3
	3.4	Modified free-water/cement ratio		X
4	4.1	Relative density of aggregate (SSD)		2.75 known/assumed
	4.2	Concrete density	Fig 5	2450 kg/m^3
	4.3	Total aggregate content	C4	2450 − 350 − 210 = 1890 kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	30 %
	5.2	Proportion of fine aggregate	Fig 6	0.43 %
	5.3	Fine aggregate content	C5	0.43 × 1890 = ~~813~~ 815 kg/m^3
	5.4	Coarse aggregate content	C5	1890 − 815 = 1075 kg/m^3

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m^3 (to nearest 5 kg)	350	210	815	240	360	480
per trial mix of .... m^3						

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm^2. 1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

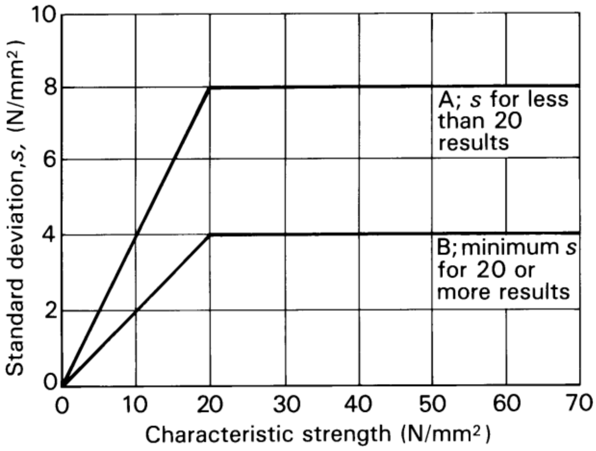

Figure 3
Relationship between standard deviation and characteristic strength

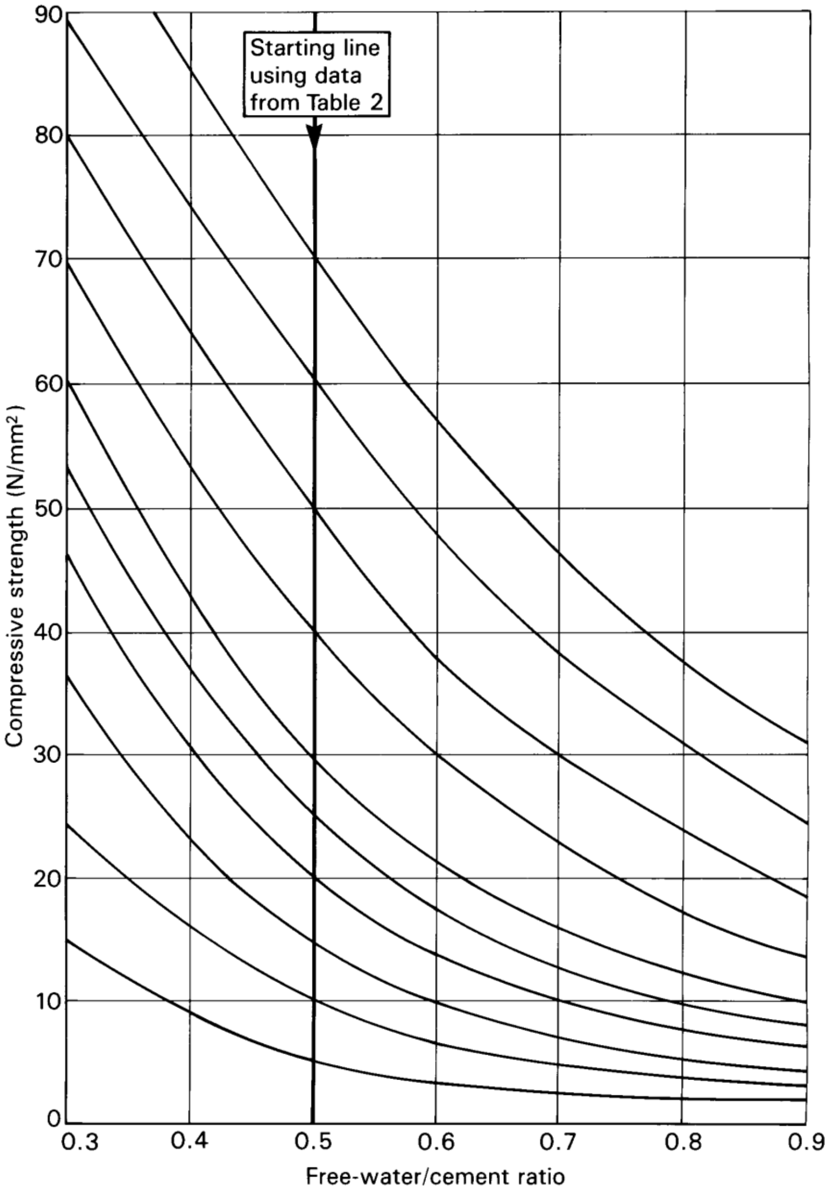

Figure 4
Relationship between compressive strength and free-water/cement ratio

Table 2 Approximate compressive strengths (N/mm^2) of concrete mixes made with a free-water/cement ratio of 0.5

Cement strength class	Type of coarse aggregate	Compressive strengths (N/mm^2) Age (days) 3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Throughout this publication concrete strength is expressed in the units N/mm^2.
1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)

Table 3 Approximate free-water contents (kg/m^3) required to give various levels of workability

Slump (mm)		0–10	10–30	30–60	60–180
Vebe time (s)		>12	6–12	3–6	0–3
Maximum size of aggregate (mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

Note: When coarse and fine aggregates of different types are used, the free-water content is estimated by the expression:

$$\tfrac{2}{3} W_f + \tfrac{1}{3} W_c$$

where W_f = free-water content appropriate to type of fine aggregate
and W_c = free-water content approporiate to type of coarse aggregate.

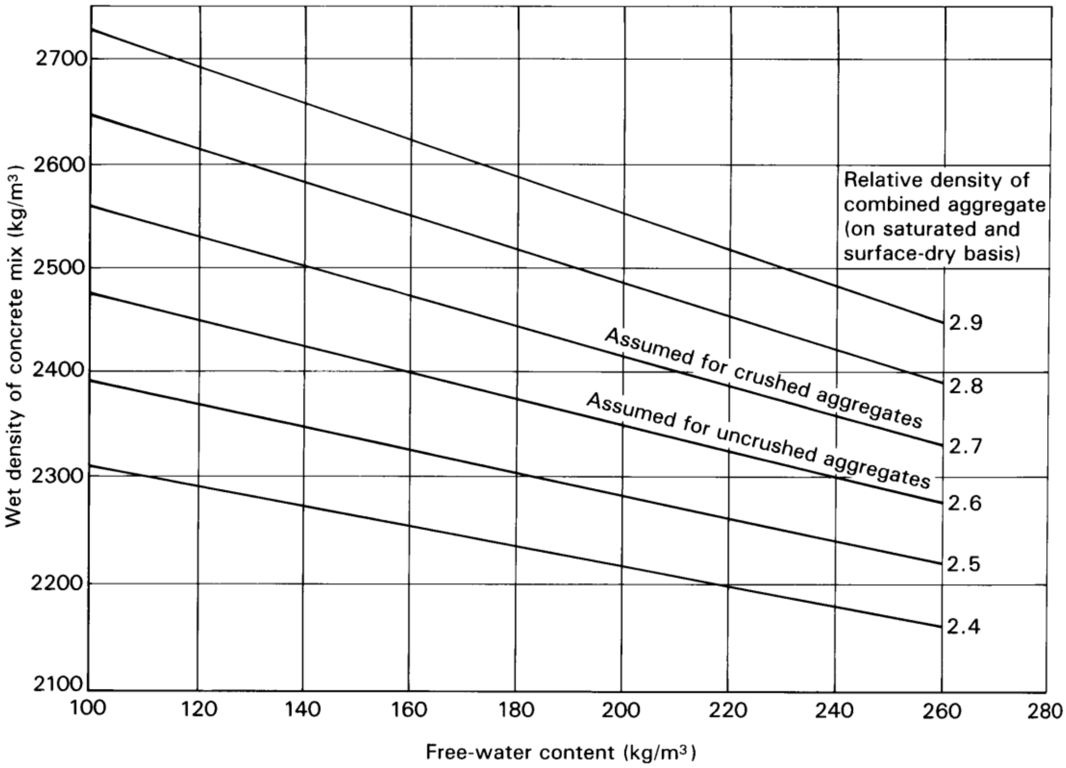

Figure 5 Estimated wet density of fully compacted concrete

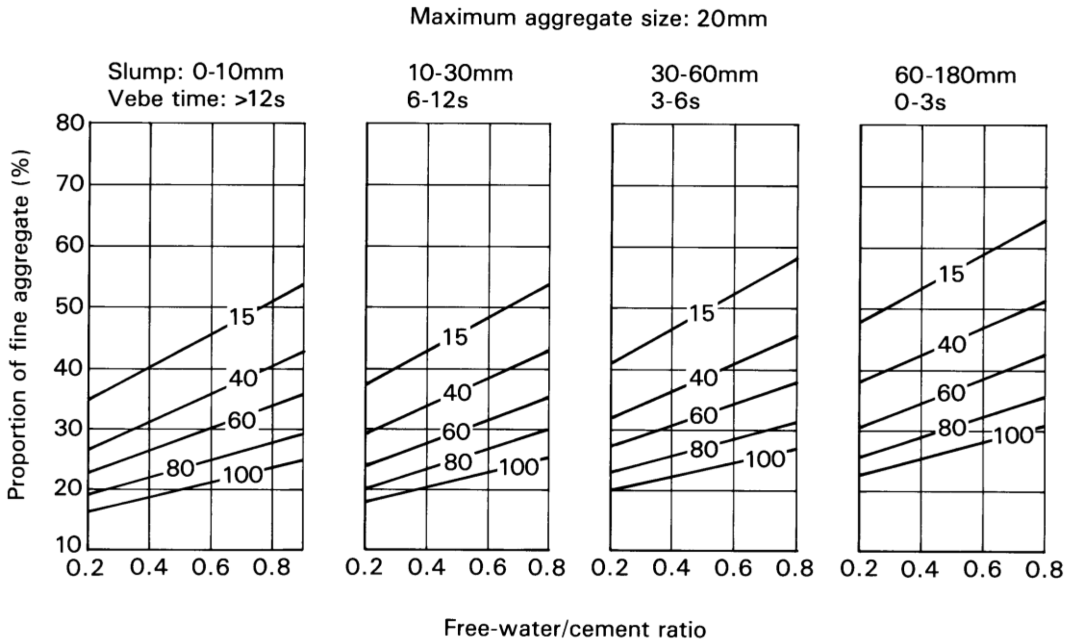

Figure 6 Recommended proportions of fine aggregate according to percentage passing a 600 μm sieve

Appendix B: Sieve Analysis Results for Fine and Coarse Aggregates According to ASTM Standards

Table 1: Sieve analysis for fine aggregates according ASTM standards

Sieve sizes (mm)	Weight retained (gm)	Percentage retained (%)	Cumulative Percent Retained	% Passing	ASTM C33-92a (%)
10	0	0	0	100	100
5	3	1	1	99	95-100
2.63	51	17	18	82	80-100
1.18	102	34	52	48	50-85
0.6 (600μm)	57	19	71	29	25-60
0.3 (300μm)	36	12	83	17	10-30
0.15 (150μm)	30	10	93	7	2-10
0.075(75μm)	21	7	100	0	-

Table 2: Sieve analysis for coarse aggregates with maximum size 10 mm in diameter

Sieve sizes (mm)	Weight retained (gm)	Percentage retained (%)	Cumulative Percent Retained	% Passing	ASTM C33-92a (%)
14	0	0	0	100	100
10	28	2.8	2.8	97.8	85-100
5	856	85.6	88.4	11.6	0-25
2.63	106	10.6	99.0	1.0	0.5
1.18	10	1.0	100	0	-

Table 3: Sieve analysis for coarse aggregates with maximum size 14 mm in diameter

Sieve sizes (mm)	**Weight retained (gm)**	**Percentage retained (%)**	**Cumulative Percent Retained**	**% Passing**	**ASTM C33-92a (%)**
20	0	0	0	100	100
14	122	4.1	4.1	95.9	85-100
10	1789	59.5	63.6	36.4	0-50
5	1071	35.7	99.3	0.7	0-10
2.63	18	0.6	100	0	-

Table 3: Sieve analysis for coarse aggregates with maximum size 20 mm in diameter

Sieve sizes (mm)	**Weight retained (gm)**	**Percentage Retained (%)**	**Cumulative Percent Retained**	**% Passing**	**ASTM C33-92a (%)**
25	0	0	0	100	100
20	557	18.5	18.5	81.5	85-100
14	1934	64.5	83	17	-
10	363	12	95	5	0-25
5	122	4.5	99.5	0.5	0-5
2.63	20	0.5	100	0	-

Appendix C: The Workability Slump Test Results for Different Proportion of Glass Gowder and Different w/b Ratios

Water Binder Ratio w/b	Cement Replacement with Glass Powder	Slump Value (cm)	Changing Compared to Control
w/b=0.4	0%	2.5	0
	10%	3.5	40.0%
	20%	5	100.0%
	30%	7.5	200.0%
	40%	4.5	80.0%
w/b=0.5	0%	1	0
	10%	1.5	50.0%
	20%	2.5	150.0%
	30%	2	100.0%
	40%	1.5	50.0%
w/b=0.6	0%	5.5	0
	10%	6.5	18.2%
	20%	7.5	36.4%
	30%	7	27.3%
	40%	6	9.1%

Appendix D: The Individual Results of Compressive Strength for Different Proportion of Glass Gowder and Different w/b Ratios

Water Binder Ratio w/b	**Cement Replacement with Glass Powder**	**Compressive Strength KN/mm2**				**Changing Compared to Control**
		Specimen 1	Specimen 2	Specimen 3	AVG	
0.4	0%	55.78	54.65	56.4	55.61	-----
	10%	58.025	55.59	65.2	59.61	7.2%
	20%	50.94	52.45	57.5	53.63	-3.6%
	30%	49.11	45.73	54.9	49.91	-10.2%
	40%	32.39	35.27	37.5	35.05	-37.0%
0.5	0%	37.46	37.97	41.5	38.98	-----
	10%	42.83	46.98	43.1	44.30	13.7%
	20%	33.04	33.1	41.4	35.85	-8.0%
	30%	29.69	33.5	29.92	31.04	-20.4%
	40%	21.62	25.25	25	23.96	-38.5%
0.6	0%	25.69	26.92	26.4	26.34	-----
	10%	30.56	31.28	32.76	31.53	19.7%
	20%	22.9	22.7	25.52	23.71	-10.0%
	30%	24.62	20.21	22.23	22.35	-15.1%
	40%	20.00	20.00	22.00	20.67	-21.5%

Appendix E: The Individual Results of Splitting Tensile Strength for Different Proportion of Glass Gowder and Different w/b Ratios

Water Binder Ratio w/b	**Cement Replacement with Glass Powder**	**Split tensile strength KN/mm2**				**Changing Compared to Control**
		Specimen 1	Specimen 2	Specimen 3	AVG	
0.4	0%	5.552	4.816	4.744	5.04	-----
	10%	5.985	5.505	5.753	5.75	14.1%
	20%	5.796	5.709	5.042	5.52	9.5%
	30%	4.91	4.782	4.589	4.76	-5.5%
	40%	4.263	3.889	4.489	4.21	-16.4%
0.5	0%	4.35	3.877	4.39	4.21	-----
	10%	4.55	4.402	4.6	4.52	7.4%
	20%	4.594	4.39	4.35	4.44	5.7%
	30%	4.594	3.988	4.339	4.31	2.4%
	40%	3.995	3.974	3.618	3.86	-8.2%
0.6	0%	2.95	3.005	4.103	3.35	-----
	10%	3.298	3.723	4.118	3.71	10.7%
	20%	3.366	3.938	3.736	3.68	9.8%
	30%	3.326	3.523	3.19	3.35	-0.2%
	40%	3.202	3.391	3.023	3.21	-4.4%

Appendix F: The Results of Modulus of Elasticity for Different Proportion of Glass Gowder and Different w/b Ratios

Water Binder Ratio w/b	**Cement Replacement with Glass Powder**	**Modulus of Elasticity (Gap)**	**Changing Compared to Control**
0.4	0%	48.39	0
	10%	54.55	12.7%
	20%	51.4	6.2%
	30%	51.22	5.8%
	40%	44	-9.1%
0.5	0%	44.91	0
	10%	45.3	0.9%
	20%	44.99	0.2%
	30%	43.55	-3.0%
	40%	35.48	-21.0%
0.6	0%	39.83	0
	10%	41.92	5.2%
	20%	42.33	6.3%
	30%	37.34	-6.3%
	40%	33.86	-15.0%

Appendix G: The Results of Water Absorption Capacity for Different Proportion of Glass Gowder and Different w/b Ratios

Water Binder Ratio w/b	Cement Replacement with Glass Powder	Percentage of Water Absorption Capacity
0.4	0	2.53
	10	2.39
	20	2.20
	30	2.35
	40	2.57
0.5	0	3.73
	10	3.66
	20	3.52
	30	3.28
	40	3.37
0.6	0	3.76
	10	3.5
	20	3.45
	30	3.83
	40	4.09