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The Effects of Shrinkage Reducing Admixtures on Shrinkage and Strength Properties of Cement Mortar Lining Mixes

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ABSTRACT

Cement mortar lining plays an essential role in protecting water supply networks. It protects the internal surface of water pipelines from corrosion and prevents the development of red-water problems in water supply networks. While several factors can cause damage to cement mortar lining, shrinkage cracks are considered one of the main sources of lining failure. Shrinkage cracks are hard to control and can significantly shorten the service life of cement mortar lining applications. Thereafter, the service life of steel pipes can be shortened due to corrosion, which in turn affects the quality of the supplied water. Controlling shrinkage is especially important in cement mortar lining of large diameter carbon steel pipelines (i.e., 48 inch - 100-inch diameter,) as shrinkage cracking of cement rich mortar linings is more pronounced in such applications. This thesis describes the effects of shrinkage reducing admixtures on the shrinkage and compressive and bending strength properties of cement mortar lining mixes. A methodology that features laboratory experiments was deemed to be the optimum approach to conduct this study. The effects of three shrinkage reducing admixtures on a reference mix were studied. The reference mix in this study is a cement mortar lining mix that is used by a pipeline engineering and construction company. This company, serving in Saudi Arabia, is also sponsoring this research project. Therefore, practices and standards used in Saudi Arabia are frequently cited in this thesis. A total of twelve mixes were designed to test the effects of using different dosages of three shrinkage reducing admixtures on the reference cement mortar lining mix. Each of the designed mixes was tested for:

1- Flow using the Standard Test Method for Flow of Hydraulic Cement Mortar (ASTM C1437).

2- Shrinkage using the Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement (ASTM C596).

Mixes that demonstrated outstanding reduction in shrinkage were also tested for compressive strength using the Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (ASTM C109); and bending strength using the German standard DIN 1164.

The study demonstrated and described the positive effect of shrinkage reducing admixtures on the shrinkage and bending strength of cement mortar lining. In addition, the results demonstrated and described the negative effect of shrinkage reducing admixtures on the compressive strength of cement mortar lining. The tested dosages of the used shrinkage reducing admixtures showed that they can reduce the drying shrinkage of a mix by 7.5 and 29.1%, decrease its compressive strength by 5 to 16%, and increase its bending strength by 4 and 16.6%

While the highest drying shrinkage reduction achieved by this study was 29.1%, the results indicated that a higher shrinkage reduction can be achieved using a higher shrinkage reducing admixture dosage. In addition, the compressive strength results showed that a shrinkage reducing admixture dosage can be used at a dosage higher than the recommended dosage by the manufacturer and the cement mortar lining mix can still meet the minimum compressive strength requirements. Therefore, it is recommended to consider shrinkage reducing admixture dosages higher than the recommended dosage range during the mix design process.

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Chapter 1: INTRODUCTION

1.1 Background

Water is considered not only essential for life, but also a cultural, social, political, and economic resource for communities. Despite this fact, many people around the world have limited or no access to unpolluted and reliable water resources (Salzman 2005). Over the past few decades, water demand has been dramatically increasing due to the rapid increase in population (Lee et al. 2018).

The water distribution network is considered the most important part of any water supply system. Therefore, approximately 80% of the total cost of any water supply project is usually invested in the water distribution system (Sarbu and Ostafe 2016). The types of materials used in manufacturing water supply pipelines are determined by various design factors, such as hydraulic, geological, static and economic conditions. In addition, other factors like cost-effectiveness ratio have to be considered when designing and selecting proper manufacturing material (Maiolo et al. 2018). The technical criteria, which determine the material type used in pipes, are directly related to the hydraulic behavior, the interaction between pipe and water, the static behavior, and the interaction between the pipe and surrounding soil (Maiolo et al. 2018).

As most water supply networks contain parts of iron composites, pipe corrosion has a huge impact on the reliability of water supply systems (Larson and Jr 2018). During the water supply process, electrochemical corrosion occurs in metal pipes due to metal electrochemical heterogeneity. After continuous corrosion, a layer of corrosion precipitation forms inside the pipe; and eventually, leads to a decrease in the inner diameter of the pipe. However, this corroded layer serves as a protection for the internal pipe layer from corrosion reactions (Atanov et al. 2018). On the other hand, corrosion in steel pipelines erodes pipe's wall leading to cracks in the pipe and water leakage (Raymond Intl 2020). The surrounding environment of a pipe can also lead to external corrosion, potentially allowing cracks to form if the pipe is not insulated properly (Atanov et al. 2018).

The quality of water can be severely affected if it is pumped through corroded pipelines. These effects can be in the form of physical or chemical characteristics like changing the color of the water to red, or reducing the chlorine and dissolved oxygen content; which creates a suitable environment for microbial growth (Sarin et al. 2001). Various water quality parameters can affect the extent of corrosion in pipelines, including but not limited to pH, alkalinity, buffer intensity, dissolved oxygen (DO), water flow characteristics, and temperature (Sarin et al. 2001).

Aging of water distribution networks leads to leakage or failure of pipelines, causing great financial loss. Several studies estimated the annual cost of water leakage in the U.S. to be between $1-2 billion (Farhidzadeh et al. 2014). The leakage issue is considered not only an economic issue, but an environmental, energy consumption and safety issue as well (Colombo et al. 2002).

Since pipeline replacement is costly and requires additional time and effort, lining technology received significant attention as an efficient solution for pipeline corrosion (Sterling et al. 2012). Lining is the application of a more corrosion resistant, premixed material to the internal face of a pipe. Pipe lining is considered the main defense against pipeline issues. It reduces internal corrosion, prevents the "red-water" problem, and maintains a smooth surface to preserve water flow capacity (With and Luk 2001) (Petronas 2017).

According to the American Water Works Association (AWWA), lining requirements differ from one system to another, depending on the purpose of the system and the environment. For instance, in the case of transporting potable water, the lining must meet toxicological requirements. In addition, an efficient lining has to be ensured over its lifespan, which requires taking into consideration additional factors such as lining resistance to chemical degradation, resistance to damage during handling, storage, and installation, and ease of repair (Petronas 2017).

Pipe lining can be applied by using a passivating (cement mortar) system or a dielectric (isolation) system. Passivating lining system is the application of cement mortar lining on the internal side of a pipeline, where the resulting alkaline cement environment protects the pipe from corrosion. Cement mortar linings are not affected or damaged by the absorbed moisture and oxygen. Dielectric lining system uses electrical and chemical isolating methods to isolate the steel pipe from the causes of corrosion. The selection process for material to be used in isolation requires evaluating the expected corrosion severity, and application and service hazards. The dielectric lining materials listed by AWWA include Nylon-11-Based Polyamide, Polyurethane, Fusion-Bonded Epoxy, Liquid Epoxy, Coal-Tar, and cement mortar (Petronas 2017). AWWA has different standards to guide the process of lining according to material types.

St. John in New Brunswick, Canada was one of the first cities in North America to install mortar-lined steel pipelines in 1855. Later, in 1963, the pipeline was removed due to relocation and found to be entirely free of corrosion after 108 years of service (Sylvia C. Hall, 2013) (Bardakjian, 1995; Bardakjian et al. 2007). In 1922, the use of portland cement mortar lining in cast-iron pipes was first introduced, because it was able to resist tuberculation at pinholes of hot-dip bituminous-lined cast-iron pipes (AWWA C104 2008). Although cement-mortar lining was first introduced in the United States in late 1800s, the first national standards for lining were not introduced until 1920s.

There are many factors that can cause damage to cement mortar lining and shorten its service life. These factors include the intermittent usage of the pipe and the consistent contact between the lining and chlorinated, soft, or aggressive waters (ANSI/AWWA 2008). In addition, flows developed in steel pipelines, with speeds over 20 ft/s and high stresses, might lead to lining corrosion with time (ANSI/AWWA 2008). In hard waters, portland cement mortar lining is not expected to be leached or carbonated, which extends the pipe's service life, typically expected to be around 100 years. The increase in water softness would lead to an increase in portland cement lining's leaching, which in turn can affect the pipe's service life and reduce it to be between 50 and 100 years (Hall 2013).

1.2 Cracks and Crazing in Cement Mortar Lining

Temperature, shrinkage, and excessive flexural stress caused by pipe mishandling or earth loads applied to the pipe, can cause cracks and crazing in cement mortar lining (Wagner et al. 2019; ANSI/AWWA 2008). Crazing appears in the form of "multidirectional fissures" which partially penetrates lining thickness. The partial penetration allows the lining to continue serving as a protector for the internal side of the pipe. AWWA standards have not specified a limitation to the presence of crazing (ANSI/AWWA C104 2008). In contrast with crazing, the term "cracks" usually refers to fissures that penetrate the whole thickness of cement mortar lining and reach the internal pipe surface. The length of cracks ranges between a few inches to several feet, extending in different directions (Wagner et al. 2019). AWWA standards state that cement mortar lining cracks with a width less than 1/16 in. do not need to be repaired. On the other hand, cracks wider than 1/16 in. need to be repaired unless it can be proved to the consumer that they can heal autogenously when continuously soaked with water (ANSI/AWWA 2008).

After the pipeline enters service, the continuous exposure of cement mortar lining to water allows the lining to absorb water and expand. The absorption of water toughens the lining and gradually closes the cracks (Sun el al. 1985, Wagner et al. 2019, and others). Autogenous healing can be detected by the gradual formation of hard white crystalline material in cracks. Experiments conducted to test crack autogenous healing demonstrate the ability of the cement mortar lining to heal under both flowing and non-flowing water (Wagner et al. 2019). Under non-flowing water, self-healing of the cracks occurs at a relatively rapid rate; crazing completely heals after approximately 60 days in water. Under flowing water conditions, the self-healing process occurs on a much slower rate; crazing completely heals in 6 months while wide cracks show a partial self-healing after one year (Wagner et al. 2019). Figure 1.1 and 1.2 show the difference between crazing and cracking in a cementitious-based material

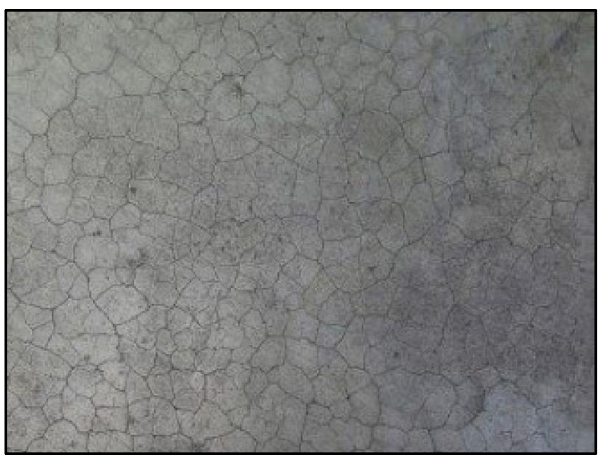


Figure 1.1 Crazing in Cementitious-Based Material (Chapman 2019)

Figure 1.2 Cracks in Cementitious-Based Material (Sarma 2017)

1.3 Shrinkage Cracks in Cementitious-Based Material

All cementitious mixtures demonstrate a tendency to shrink (Li 2017). Shrinkage in cementitious-based mixtures is the dimensional change of the mixture after placement. It occurs in two main stages, plastic shrinkage (early age shrinkage) and drying shrinkage (later age shrinkage) (Wang 2011). Plastic shrinkage occurs due to evaporation of water in the mixture within the first hours after placing it and before it starts to gain significant strength (Wang 2011 and Filho et al. 2005). Drying shrinkage occurs at a later stage as the mixture starts gaining strength. Drying shrinkage has been ascribed to the loss of internal moisture of the mixture. As the mixture gains more strength, negative capillary pressure develops leading to transport of the mix's internal moisture to the surface of the placed mixture (Wang 2011 and Filho et al. 2005).

As the mixture shrinks, shrinkage cracks start to develop in the cement paste. This happens when the stress caused by shrinkage starts to exceed the tensile strength of the mixture. While plastic and drying shrinkage contribute to the development of shrinkage cracks, the effect of plastic shrinkage is significantly less than the effect of drying shrinkage (Wang 2011). Drying shrinkage in a cementitious-based material is affected by several factors that can be categorized into two main groups; material features and ambient conditions. The first group of factors include the characteristics and properties of the materials used in the mix; such as the water/cement ratio, aggregate properties, type of cement, air content, and mixture additive (admixtures). The ambient conditions in the second group are the environmental conditions where the mixture is cast and cured such as temperature, humidity, wind speed, ... etc (Wang 2011).

1.4 Problem Statement

Among all the factors that can cause damage to cement mortar lining, shrinkage cracks are considered the hardest to control and the most common cause of pipe failure (Wagner et al. 2019). Shrinkage cracks can penetrate the full thickness of cement mortar lining, allowing water to reach to pipe's internal surface causing corrosion (Wagner et al. 2019). As a result, the quality of supplied water and the service life of a water supply pipeline can significantly deteriorate. In addition, the rate of water leakage from a water supply network can increase (Larson and Jr 2018).

Shrinkage in cement mortar depends not only on the proportions and characteristics of used materials in the mixture, but also on the environmental conditions that surround the mixture while mixing and placing. A hot and dry environment increases shrinkage as the evaporation rate in the mixture increases (Wang 2011). This fact makes controlling shrinkage cracks in cement mortar lined pipes particularly critical in countries that constantly have hot and dry weather year-round. The ambient conditions in such countries are hard to control while mixing and placing cement mortar, which increases lining shrinkage, and subsequently the chance of developing shrinkage cracks. Keeping the above in mind, it is obvious that there is an essential need to reduce shrinkage in cement mortar lining to limit and reduce development of shrinkage cracks.

1.5 Research Objectives

This research focuses on cement mortar lining shrinkage and the subsequent shrinkage cracks. The main objective of this research is to investigate the effects of using shrinkage-reducing admixtures on shrinkage and strength properties of cement mortar lining used in water supply pipelines. In addition, the flowability of the mix is taken into consideration to ensure the mixture can be applied and sprayed with ease. The final outcome of this research is a cement mortar mixture to be used in lining of water supply pipes with low drying shrinkage, adequate flowability, and high compression and bending strength.

1.6 Thesis Structure

Chapter 2 sheds light on the standardized procedures for lining and curing cement mortar lined pipes. In addition, it studies the factors that affect properties of the fresh and hardened cement mortar mixtures, as well as the tests required to ensure the reliability of cement mortar lining. Chapter 3 discusses the experimental methodology followed in this research and the rationale behind choosing this approach. Chapter 4 presents the results obtained, and Chapter 5 discusses the results and examines their validity. Finally, Chapter 6 concludes the thesis, summarizes the findings, and proposes recommendations for future research.

Chapter 2: LITERATURE REVIEW

2.1 Pipeline Lining Process

2.1.1 Mortar Lining Thickness

Cement mortar lining thickness is determined based on pipe type and diameter using the American Water Works Association (AWWA) standards. The thickness of cement mortar lining should be uniform throughout the pipe; this has to be ensured by physical measurements (ANSI/AWWA 2008). Table 2.1 summarizes the required lining thickness for water pipelines based on pipe type and diameter.

Table 2.1 Thickness of Mortar Lining in Water Pipelines (ANSI/AWWA 2008)

Pipe Type	AWWA Standards	Diameter Range, inch (mm)	Nominal Lining Thickness, inch (mm)
Steel Pipe	C 205	4 to 10 (100-250)	1/4" (6)
		11 to 23 (275-575)	5/16" (8)
		24 to 36 (600-900)	3/8" (10)
		Over 36 (over 900)	1/2" (13)
Ductile Iron Pipe	C151/C104	3 to 12 (76-305)	1/16" (1.6) min.
		14 to 24 (356-610)	3/32" (2.4) min.
		30 to 64 (762-1600)	1/8" (3.2) min.
Concrete Cylinder Pipe (CCP)	C303	10 to 16 (250-400)	1/2" (13)
		18 to 72 (450-1830)	3/4" (19)

2.1.2 Mortar Lining Application

There exist two basic techniques for the application of cement mortar lining. The first technique is known as the centrifugal or “Centriline” process. This process requires the use of a lining machine which applies mortar at a consistent rate along the internal surface of a stationary pipe. Another method of lining is the spinning method, which is best suited for lining straight or round pipes. In this method, the pipe undergoes a quick rotation on a belt or rubber tires as the mortar is applied over the internal surfaces at an uneven rate which can result in white spots (ANSI/AWWA 2008).

Both methods of linings can be used; however, there are certain differences that one must consider if looking for a preferred result (i.e. quality vs quantity). The primary difference between the two linings is that centrifugal linings are denser, containing about two to three times the amount of cement held by spun linings. This results in a cleaner and more uniform distribution of mortar with almost no segregation or white spots as a spun lining would show. Since centrifugal linings contain more cement, the extra cement can help to form a chemical and mechanical barrier and also a "zone of alkalinity" on the interior surface of the pipe (ANSI/AWWA 2008).

2.1.3 Mortar Lining Curing

Upon the completion of lining, the pipe should be carefully moved to a curing place, where the curing process should start no later than 30 minutes after the lining process is complete. Curing can be done using moist curing, accelerated curing, or a combination of both with a time ratio of $5\frac{1}{3}$ hours of moist curing to 1 hour of accelerated curing (ANSI/AWWA 2008).

2.1.3.1 Moist Curing

According to AWWA standards, moist curing can be used only in cases where the ambient temperature exceeds 40° F during the whole curing process. The lining should be kept moist for a total curing time of more than 96 hours with closing the two ends of the pipe with plastic or wet burlap. In case of applying a coating, the pipe should be moist cured for a minimum of 24 hours before applying the coating, and the total curing time should be 96 hours (ANSI/AWWA 2008).

2.1.3.2 Accelerated Curing

Water vapor is used in the accelerated curing process to cure lining. The ambient vapor temperature should be maintained between 90° F and 135° F with a relative humidity not less than 85% for a total curing time of 18 hours. The temperature of the pipe should not exceed 95 F° for the first 4 hours or until the cement mortar takes its initial set, whichever is shorter (ANSI/AWWA 2008). After finishing the curing process, all general defects, such as sand pockets, voids, over sanded areas, and blisters, should be eliminated and relined with the same lining thickness. Cracks less than 1/16 in. wide do not need to be treated. Cracks wider than 1/16 in. can heal autogenously under consistent soaking; and there is no need to treat them if the producer can demonstrate this fact to the purchaser (ANSI/AWWA 2008).

2.2 Cement Mortar Lining Mix Ingredients and Characteristics

The American Water Works Association standards list cement, fine aggregate, and water as the main components of a cement mortar mixture to be used in pipe lining. However, cement mortar mixture can also contain admixtures upon obtaining the purchaser’s approval, as long as the admixtures do not contain any injurious amount of chlorides (ANSI/AWWA 2008). For potable water pipes, any addition to the mix, including admixtures, must be checked to ensure that it contains no chemicals that would contaminate the water flowing through the pipes. To ensure each admixture or ingredient added to the mix is approved for potable water use, information and certification must be obtained from the manufacturer stating that the admixture is approved for use with potable water. If the admixture is not approved, the cement mortar mix cannot be used, even if it proves successful in reducing the shrinkage of the lining (ILF 2015).

According to AWWA standards, the cement used in cement mortar lined pipes should be Ordinary Portland Cement (type I) that conforms to ASTM C150 requirements. In addition, the fine aggregates used should consist of dry natural sand or sand obtained from crushed gravel or stone and it should conform to ASTM C33 standards (ANSI/AWWA 2008).

While AWWA standards do not require specific gradation for the used fine aggregate, the cement mortar lining specification used in Saudi Arabia (M03) require using dry sand graded between 1.25 mm and 0.125 mm with a 100% passing the 1.25 mm sieve. In addition, it requires the sand to be free of any injurious amounts of dust, clay lumps, friable particles, mica, loam, oil, alkalis and other deleterious substances. The limits of parameters allowed in sand are shown in Table 2.2.

Table 2.2 Parameters Limits Allowed in Sand (ILF 2015)

Parameter	**Limit**
Clay Lumps and Friable Particles	Maximum 1%
Material Finer Than 75 Microns	Maximum 2%
Organic Impurities	Higher Than Standard
Water Absorption	Maximum 1.5%
Chloride Ion Content (CI)	Maximum 0.05%
Sulphates (SO_3)	Maximum 0.4%
Magnesium Sulphate Soundness	Maximum 10%
Potential Alkali Silica Reactivity	Innocuous According ASTM C289
Specific Gravity (Unit Weight)	According ASTM C128

The water used in the cement mortar mix and for curing shall conform to the applicable requirements of the ASTM C94 standard. On the other hand, the cement mortar lining specification used in Saudi Arabia (M03), requires using mixing and curing water that conforms to the German standard DIN 1045, putting limits to water parameters as shown in Table 2.3.

Table 2.3 Water Parameters Limits (ILF 2015)

Parameter	Limit
pH	7 - 8
Total Dissolved Solids	Maximum 2000 Ppm
Suspended Solids	Maximum 500 Ppm
Chloride as CL Ion	Maximum 500 Ppm
Sulphates as SO_3	Maximum 1000 Ppm
Alkali Carbonates and Bicarbonates	Maximum 1000 Ppm

2.3 Testing Cement Mortar Mixture

The American Water Works Association (AWWA) standards require testing only mortar's compression strength as a measure of lining durability (ANSI/AWWA 2008). However, specifications in other countries require a larger set of laboratory tests to ensure the durability of cement mortar used in pipe lining. For instance, the cement mortar lining specifications used in Saudi Arabia require testing mortar lining in terms of compressive strength, bending tensile strength, chemical composites, blain value, and density (ILF 2015). The mix-design process of cement mortar can involve a wider range of tests that investigate many properties of the fresh and hardened mix (ILF 2015). This research will focus on studying the flowability, shrinkage, and compressive and bending strength of cement mortar mixes.

2.3.1 Fresh Mix Tests

The properties of the fresh mix reflect its ability to be easily applied to a pipe's internal surface. The Standard Test Method for Flow of Hydraulic Cement Mortar (ASTM C1437) is used to determine the mix flowability. Although the flowability is not part of the hydraulic cement specifications, it is usually tested for applications that require a certain water content and workability.

2.3.1.1 Standard Test Method for Flow of Hydraulic Cement Mortar (ASTM C1437)

Flowability is the common term that is used to describe the workability of cement mortar. ASTM C1437 standards are used in measuring the flowability of hydraulic cement mortar and mortars with other cementitious materials. The test is performed using a tamper that conforms to the ASTM C109 standard, a flow mold, a flow table, and a caliper that conforms to the ASTM C230 standard. The test is performed by casting the cement mortar mix in two layers in the mold and tamping each layer 20 times using the tamper. The mold shall be removed after 1 minute of filling it with the mortar mix. The flow table shall be dropped 20 times within 15 seconds, making the molded cement mortar spread and have a new certain diameter. Careful attention has to be paid during performing the test as the water within the cement mortar mix must be maintained. The flow is expressed as the percentage between the mix's new diameter resulting from the drop and the mold's original diameter (ASTM C1437 2015).

2.3.2 *Hardened Mix Tests*

2.3.2.1 Drying Shrinkage of Mortar Containing Hydraulic Cement (ASTM C596)

The ASTM C596 test method is used to measure the length change for the cement mortar specimen due to air drying. The standard establishes a set of conditions to which a cement mortar specimen shall be subjected for a period of time. These conditions include temperature, relative humidity, and rate of evaporation. In addition, the ASTM C596 standard refers to a set of other ASTM standards that has to be taken into consideration during this test (ASTM C596 2001).

According to ASTM C596 standards, curing and storing a cement mortar specimen should be done in conformance with ASTM C490 standards (ASTM C596 2001). In addition, ASTM C490 explains the use of an apparatus for the determination of length change of hardened cement paste, mortar, and concrete. This examination allows finding the deformation that may occur along the longitudinal axis due to external forces. The standard uses a length change apparatus (LCA) and a reference bar to test length change in a 25 x 25 x 285 mm specimen. The approximate time for completion for this experiment ranges from one to several weeks depending on the accuracy desired (ASTM C596 2001).

First, the specimen mold is prepared by sealing it from the outside and also lining the interior walls with mineral oil. The cement mix is then placed into this mold and secured in place to cure for 24 or 48 hours, depending on when the specimen gains sufficient strength that allows taking it out of the mold. When the mix gains sufficient strength, the sample is removed from the molds and left to cure for 48 hours in a curing chamber that conforms to ASTM C511 standards. Following the curing process, the bar is set on the LCA to take a reference reading. After recording the reference reading, the specimen is left to air dry in conditions that conforms to ASTM C596. The specimen length readings shall be taken after 4, 11, 18, and 25 days of air storage. In order to calculate the length change, the following equation must be used,

$$L = \frac{(L_x - L_i)}{G} \times 100$$

where L is the length change (%), L_X is the difference between a comparator reading of the specimen and the reading of reference bar (mm), L_i is the difference between the initial comparator reading of the specimen and the initial comparator reading of the reference bar (mm), and G is the nominal gauge length (250 mm) (ASTM C596 2001; ASTM C490 2011).

It is expected that when samples undergo the length change test (ASTM C490), they will experience hairline cracks. This is acceptable as long as the hairline cracks or surface cracks do not exceed a width of 0.8mm and a length greater than 50% of the pipe length (Harper 2018). This test will be used to establish the mix proportions that will produce the lowest possible shrinkage values (Harper 2018). It shall be conducted on a weekly basis or on the 7th, 14th, and 28th days. Figure 2.1 and 2.2 show pictures of the process of measuring the drying shrinkage.

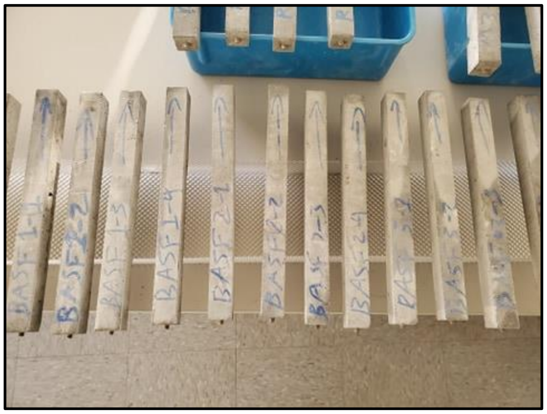


Figure 2.1 Specimen Cast According to ASTM C596

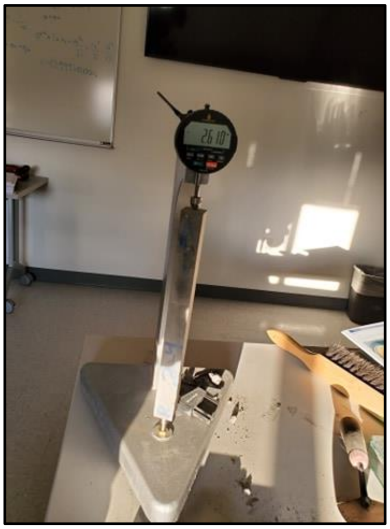


Figure 2.2 Using Length Gauge to Determine the Change of Length with Time

2.3.2.2 Compressive Strength (ASTM C109)

ASTM section C109/C109M -16a describes the standard test method to determine the compressive strength of hydraulic cement mortars. Through this test method the compressive strength of mortar can be determined, which can be used to check if the strength of the mortar meets specific standards and target values (ASTM C109 2010).

To conduct this test, a two-inch cube mortar specimen is prepared according to ASTM C305. Upon preparing the mixture, ASTM C109 standards require conducting a flow test according to ASTM C1437. When the flow test is completed, the mortar needs to be remixed for 15s to prepare the mix to cast the test specimens. To do this, the mortar is placed in the molds, one inch deep. Each cube must be tamped 32 times within 4 cycles, alternating the direction of tamping in each cycle. After the first layer is tamped, the second layer is placed and tamped following the same method. Once all cubes are cast, the mold is leveled with a tamping rod, then placed in a moist room for curing. Specimens have to be tested at 24 hours, 3 days, 7 days, and 28 days or as needed. The 24-hour test specimens are left in the moist room until testing. However, the other test specimens are placed in storage tanks that contain saturated lime water at 73 F° until their respective test time. To test each specimen, it is placed in the testing machine, allowing the load to be applied to the side of the specimen that was in contact with the bottom of the mold. The load is then applied to the specimen at a range of 200 to 400 lb/s, and the maximum load before failure is recorded. To calculate the compressive strength of the specimen the following equation is used:

$$f_m = \frac{P}{A},$$

where f_m = compressive strength in psi, P = maximum load in lbf, and A = area of loaded surface in^2. The compressive strength should be calculated to the nearest 10 psi (ASTM C109 2010). Figure 2.3 shows the process of measuring the compressive strength of specimen using an automated machine.

Figure 2.3 Measuring the Cement Mortar Compressive Strength Using an Automated Machine

According to AWWA specifications, the minimum compressive strength required for a cement mortar lining at the age of 28 days is 31 MPa (ANSI/AWWA 2008). However, the cement mortar lining specification used in Saudi Arabia has a stricter strength requirement. Cement mortar lining should have a minimum compressive and bending strength of 55 MPa and 6 MPa respectively at an age of 28 days (ILF 2015).

2.3.2.3 Bending Strength (DIN 1164)

DIN 1164 Part 7 provides specifications to test specimens for bending strength using a flexural tensile strength test. Through this test the maximum resistance of the specimen when placed under bending conditions are determined. After preparing the mortar mixture, the mold must be clamped onto a vibration apparatus before filling it with the mortar. The mortar is then added to the mold halfway deep within 15 seconds, followed by waiting for another 15 seconds to add the rest of the mortar. Once all the mortar is added into the molds, the vibration shall be applied for a total of 120 seconds. The tops of the molds are then leveled. The specimens are, then, placed in a moist room and taken out of their molds after 24 hours. Once the specimens are out of their molds, they are placed in still water until their respective testing time. At the desired testing time the specimen is placed on its side, centered on the machine supports. The load should, then, be applied on the specimen at a constant rate until rupture. To calculate the final bending strength, the following equation is used:

$$B = 2.34 \text{ x } 10\text{-}3 * F,$$

where B is the bending strength and F is the maximum load before rupture.

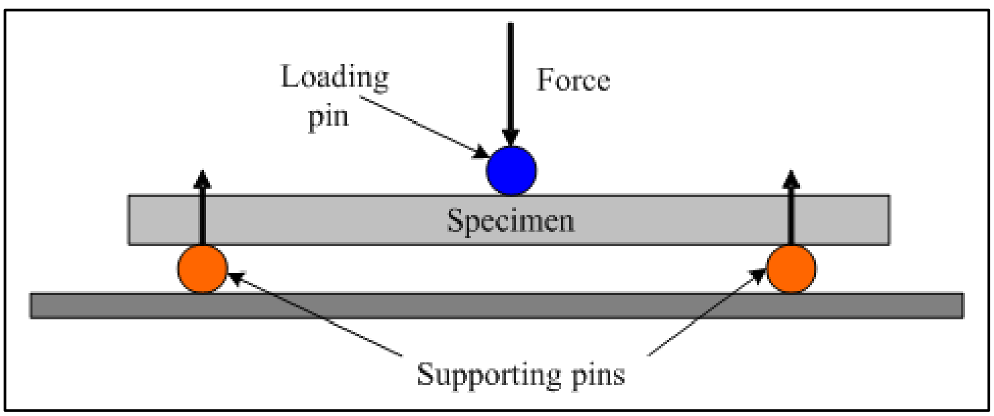


Figure 2.4 Three-Point Bending Test (Ćurković et al. 2010)

2.4 Factors Affecting Cement Mortar Properties

Neglecting the effects of external conditions like weather, cement mortar lining properties are mainly affected by water/cement ratio, cement/sand ratio, sand fineness modulus, and admixtures (Mollo 2015; Ikotun and Ekolu 2010; Yuan et al. 2014).

2.4.1 Water/Cement Ratio

Cement works as a cohesive material within a cement mortar mix by establishing a strong attachment between the ingredients of the mix. Increasing water/cement ratio increases cement mortar workability. It also increases the porosity of cement mortar mix and the risk of stratification and segregation. This, in turn, leads to a reduction in the mixture's density and ultimate compressive strength (Kim et al. 2014; Yuan et al. 2014). In addition, higher water/cement ratio results in higher water permeability, chloride diffusion, and the penetration of chloride ions in the hardened cement mortar (Kim et al. 2014). As chloride ions are considered the main cause of steel pipe corrosion, if cement mortar lining is not strong enough to resist chloride ion penetration, the installed lining would be ineffective and corrosion in the internal face of a steel pipe would still occur.

According to AWWA standards, the water content of cement mortar lining mix shall not be less than 7% of the dry weight of the mixture. In addition, an excessive amount of water should be avoided and the water-soluble chloride ion (Cl-) shall not exceed 0.15% by weight (ANSI/AWWA 2008).

2.4.2 Cement/Sand Ratio

Sand is the main contributor to the strength of cement mortar by carrying out most of the external applied loads (Mollo 2015). According to Mollo (2015), increasing cement content enhances mortar strength up to a cement/sand ratio of 0.3:0.4. In this range, most voids within compacted sand is filled with cement, which increases mortar's compressive strength. Increasing the cement/sand ratio beyond 0.6:0.7 makes the sand very dispersed in the cohesive material (the cement) to a point where it no longer contributes in carrying out load, and as result, it reduces the mortar compressive strength. At this point, the mortar's compressive strength is equal to the cement compressive strength (Mollo 2015). According to AWWA standards, cement mortar lining mix should contain one part of cement to not more than three parts of fine aggregate by weight (ANSI/AWWA 2008)

2.4.3 Sand Fineness Modulus

Sand fineness modulus has an inverse relationship with cement mortar compressive strength. Higher fineness modulus requires using a higher water/cement ratio to ensure proper workability of the mix, as result, the ultimate compressive strength of the mix decreases (Reddy et al. 2008).

2.4.4 Admixtures

Various types of admixtures can be added to cement mortar or concrete mixes in accordance with the mix's use. Admixtures are categorized based on the purposes of their use. These categories include, but are not limited to, water-reducing agents, retarders, air-entraining agents, accelerators, expansion agents, and water-proofing agents (Gutcho et al. 1980). According to AWWA standards, water-reducing and set-controlling admixtures can be added to cement mortar mix while conforming to ASTM C494. The added admixture should not contain any harmful amounts of chloride. Other types of admixtures can also be added but only after their effects and impacts have been studied (ANSI/AWWA 2008).

2.4.4.1 Water-Reducing Admixture

The workability of cement mortar and concrete mixes is mainly affected by the amount of water used in the mix (water/cement ratio). Water-reducing admixtures are used to reduce the amount of needed water to obtain a mix with certain workability (Gutcho et al. 1980; ASTM 2015). Water-reducing agents typically reduce 5-10% of water content required to obtain a certain desired slump. As a result, water-reducing agents generally increase the strength of a mix due to the reduction in the water-cement ratio (Kosmatka et al. 2002). In case of using water-reducing admixtures and maintaining the same water content, a significant increase in slump would result and the ultimate strength of the mix is expected to remain the same or decrease (Whiting and Dziedzic 1992). Although the use of water-reducing admixtures increases the workability of the mix, such admixtures may also cause a small increase in its drying shrinkage after setting (Kosmatka et al. 2002).

Water-reducing admixtures are divided into three categories: normal, mid-range, and high-range admixtures. Mid-range and high-range water reducing admixtures can provide much higher slump than normal water-reducing admixtures. In addition, high-range water-reducing agents, which are referred to in ASTM C494 as type F (high-range water-reducing) and type G (water-reducing and retarding), can produce a concrete mix with ultimate compressive strength that exceeds 70 MPa, reduces chloride-ion penetration, and increases early strength gain (Kosmatka et al. 2002).

2.4.4.2 Retardants

Retarding agents are used to delay the mix setting time to allow more time for proper casting and finishing. As the high temperature of the fresh mix accelerates the rate of hardening, retardants are used to offset the accelerating effect of hot weather and to allow more time for casting and finishing processes. In addition to using retarding admixtures, a mix can be retarded by cooling the aggregates and water used in the mix, reducing the temperature of the fresh mix. Furthermore, retarding admixtures cause a reduction in the strength of a mix during its early hardening stages as they delay the reactions between cement and water and extend the mix setting time. Shrinkage and other properties of a mix cannot be anticipated. Tests have to be conducted to check for these effects (Kosmatka et al. 2002).

The use of retarding agents is not limited to delaying the setting time of cement mortar and concrete mixes, but is also used to increase the slump of the mix, which in turn, increase the workability of a mix (Whiting and Dziedzic 1992).

2.4.4.3 Shrinkage-Reducing Admixtures

Shrinkage-reducing admixtures are used where cracks need to be minimized for durability and aesthetic purposes (Passuello et al. 2009; Kosmatka et al. 2002; Hwang and Khayat 2009). Two types of shrinkage reducers are usually used, propylene glycol and polyoxyalklene alkyl ether. According to conducted laboratory tests, drying shrinkage reducing admixtures typically reduce shrinkage by between 25% and 50% (Passuello et al. 2009; Kosmatka et al. 2002).

2.4.4.4 Micro-Silica

Micro-silica, also known as silica fume, is a very fine by-product material generated from the production of silicon. It is considered as one of the most widely used cementitious materials in producing high-strength and high-performance concrete and cement mortar (Li et al. 2017). Adding micro-silica to cement mortar and concrete mixes improves the properties of fresh and hardened mixes in terms of durability, workability, strength, and permeability (Bolhassani and Samani 2015). According to the specification used in Saudi Arabia by the cement mortar lining company sponsoring this research, silica fume used in cement mortar lining must conform to ASTM C1240 standard requirements. In addition, micro-silica has limits on its composites. Table 2.4 illustrates the limits of micro-silica parameters according to the requirements in Saudi Arabia.

Table 2.4 Limits of Micro-silica Composites (ILF 2015)

Parameter	**Limit**
SiO_2 Content	Minimum 90%
Moisture	Maximum 3%
Loss of Ignition	Maximum 4%
Alkali Content	Maximum 1.5%
Accelerated Strength Activity	Minimum 105%
BET Surface Area	Minimum 15000 m^2/kg
SO_3	Maximum 2%
MgO	Maximum 5%
Chloride	Maximum 0.1%
Free Si	Maximum 0.4%
Fineness (larger than 0.045 mm)	Maximum 40%
Free CaO	Maximum 1%

Chapter 3: METHODOLOGY

The objective of this research is to study the effects of shrinkage reducing admixtures on the drying shrinkage, compressive strength and flexural bending strength properties of cement mortar lining. An investigation based on laboratory testing is the selected approach to achieve this objective. The effects of three different shrinkage reducing admixtures are studied by generating new mixes in which each admixture is added to a reference cement mortar mix, respectively. Figure 3.1 illustrates the methodology that is followed in this research.

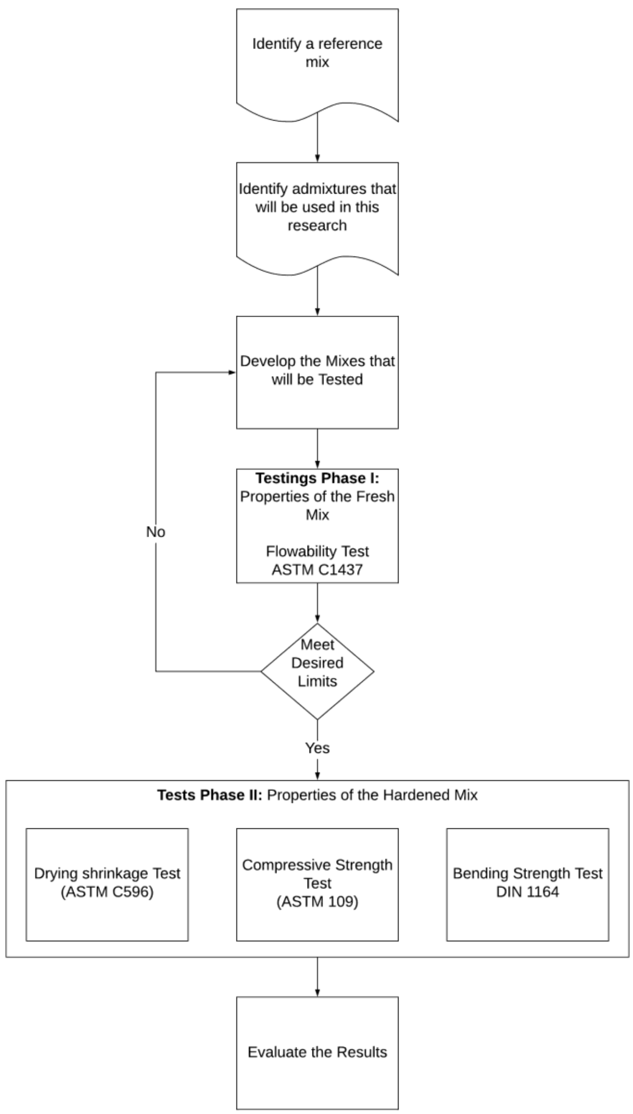


Figure 3.1 Research Methodology

3.1 Reference Mix

The properties of fresh and hardened cementitious-based mix are determined by its mix design (i.e., ingredients and the ratios of ingredients) (Mollo 2015; Ikotun and Ekolu 2010; Yuan et al. 2014). Therefore, it is necessary to fix the ingredients and ratios of cement mortar lining mix in order to study the effects of adding shrinkage reducing admixtures. This mix with fixed ingredients and ratios in this research will be called the reference mix.

While the AWWA specifications do not offer detailed guidance on the ingredients and ratios of cement mortar mixes to be used in pipe lining, the cement mortar lining specification used in Saudi Arabia suggests using a mix made of cement, sand, water, micro-silica, and retarding/water-reducing admixture. According to the specification (ILF 2015), the maximum permissible water to cementitious material (cement + micro-silica) ratio is 0.32. The retarding/water-reducing admixture in the mix is used to compensate for the low water to cementitious material ratio and to maintain an adequate level of flowability. The micro-silica (silica fume) content in the mix should be between 5 to 8% of the cement weight. The recommended micro-silica content is 7%, as it is shown to yield the best strength and shrinkage properties (IFL 2015).

In this research, the reference mix that will be adopted will conform to the cement mortar lining specification used in Saudi Arabia. Table 3.1 illustrates the ingredients and ratios of a cement mortar lining mix that is used by a pipeline engineering and construction company in Saudi Arabia. This mix will be the reference mix adopted in this research.

Table 3.1 Reference Cement Mortar Lining Mix

Mix Name	Ingredients	Parts by Weight
Reference Mix	Cement	1
	Sand to Cement ratio	1.18
	Water to Cementitious Material (cement + micro-silica) Ratio	0.32
	Micro-Silica (% of cement)	7%
	Water-Reducing Admixture (mL/kg cement)	2.1 mL/kg of cement

The water-reducing admixture used in the reference mix is a plasticizer and retarder used to improve the flowability of mortar without increasing the water to cement ratio. The admixture has the ability to increase the compressive, tensile, and flexural strength of the mortar or concrete by lowering the water to cement ratio needed to achieve the desired flowability. In addition, it increases the density of the mix and improves its water permeability. The product has no potential effect on drying shrinkage properties of the mix (Fosroc 2019). The water reducing admixture dosage in the reference mix is used to achieve a flowability of 55.1% and 66.6% (Aguilar 2018).

3.2 Admixtures Used in this Research

The type and quantity of admixtures added to the reference mix affect the characteristics of the fresh and hardened cement mortar mix. With the exception of the reference mix, all mixes studied in this research contain two types of admixtures: a water reducing admixture and a shrinkage reducing admixture.

3.2.1 Shrinkage Reducing Admixtures

Three commercial shrinkage reducing admixtures are used in this research to study their effects on cement mortar lining mix: Sika Control NS, BASF MasterLife CRA 007, and BASF MasterLife SRA 035.

Sika Control NS is a shrinkage reducing/compensating admixture that meets the requirements of ASTM C-494 Type S. It is usually used to produce high performance concrete with reduced water impermeability and potential for drying shrinkage cracking and curling. According to the product data sheet, the admixture does not affect the flowability, setting time, or the compressive and bending strength of the mix. The recommended dosage range for Sika Control NS admixture is 2–7 % by weight of cement mass used in the mixture (Sika 2018).

BASF MasterLife CRA 007 is a crack/shrinkage reducing admixture that meets ASTM C-494 Type S Standard Specification for Chemical Admixtures for Concrete. The admixture is used to reduce the magnitude of drying shrinkage and minimizes the potential for cracking in cement-based material. The data sheet of the product suggests that it can significantly reduce the potential of shrinkage cracking and initial crack widths if cracking does occur. While the product is not expected to affect the flowability of the mix, the admixture can cause a slight reduction in the compressive strength of the mix. The recommended dosage range of MasterLife CRA 007 admixture is 5 to 10 L/m3 of the mixture (BASF Corporation 2018). Assuming that the average density of cement mortar is 2162 kg/m^3 and since the ratios of the reference mixture are known, the recommended dosage of the admixture can be estimated to be 1 to 10 mL/kg of cement weight.

BASF MasterLife SRA 035 is a shrinkage-reducing admixture that meets the ASTM C 494 requirements Type S. The admixture reduces drying shrinkage of concrete and mortar, and the potential for subsequent cracking by reducing capillary tension of pore water in the mixture. Similar to other shrinkage reducing admixtures, the product does not have any effect on the flowability of mix. However, it can cause minimal reduction of the mix's compressive strength. The typical dosage range of MasterLife SRA 035 admixture is 2.5 to 7.5 L/m3. Assuming that the average density of cement mortar is 2162 kg/m^3 and since the ratios of the reference mixture are known, the typical dosage range of the admixture can be estimated to be 2 to 9 mL/kg of cement weight.

3.2.2 Water Reducing Admixtures

As previously mentioned, reference mix adopted in this research contains water reducing admixture to achieve a flowability between 55.1%-66.6% while maintaining a water to cementitious material ratio of 0.32. Therefore, all mixes tested in this research shall contain a water reducing admixture that achieves the same flowability. The data sheets of the selected shrinkage reducing admixtures suggest that they should not be used in the same mix with admixtures from different manufacturers. This is to avoid any unexpected effects on the properties of the mix (Sika 2019) (BASF Corporation 2019). Thus, the water-reducing admixture used in the reference mix shall be replaced with a water reducing admixture from the same manufacturer of the shrinkage reducing admixture tested in each mix. Two water reducing admixtures were found to be proper replacements for the admixture used in the reference mix; these admixtures are Sika Viscocrete 2100 and BASF MasterGlenium 7920.

Sika Viscocrete 2100 is a high range water reducing and super-plasticizing admixture that may be used in both ready-mix and precast applications. The admixture meets the requirements for ASTM C494 Types A and F. Sika Viscocrete 2100 can be used in small doses to obtain water reduction from 10-15%, or in high dosages to achieve water reduction up to 45%. According to the admixture data sheet, the used dosage can vary according to materials used, ambient conditions and the requirements of a specific project. The typical dosage range recommended by the manufacturer is 0.65–3.9 ml/1 kg of cementitious materials (Sika 2018).

BASF MasterGlenium 7920 is a high-range water reducing admixture that increases the flowability of the mix without increasing the water to cement ratio. The admixture meets the requirements for ASTM C494 Types A and F. BASF MasterGlenium 7920 works on rapidly dispersing powder materials in concrete mixtures, thereby minimizing mixing time. According to the data sheet, the typical dosage can range between 1.3 and 7.8 mL/1 kg of cementitious materials. However, dosages that range between 1.3 and 5.2 mL/1 kg is proved to provide excellent performance in most mixes (BASF Corporation 7920 2018).

3.3 Test Mixes

In addition to the reference mix, three groups of cement mortar mixes were designed to be tested in this research. Each of the three groups will study the effects of adding different dosages of one of shrinkage reducing admixtures. The four added dosages of each shrinkage reducing admixture cover the range suggested by the admixture data sheet. Mixes in group 1 contain Sika Control NS shrinkage reducing admixture and Sika Viscocrete 2100 water reducing admixture. Mixes in group 2 contain BASF MasterLife CRA 007 shrinkage reducing admixture and BASF MasterGlenium 7620 water reducing admixture. Mixes in group 3 contain BASF MasterLife SRA 035 shrinkage reducing admixture and BASF MasterGlenium 7620 water reducing admixture.

Tables 3.2, 3.3, and 3.4 illustrate the ingredients, ratios, and the admixture dosages used in each mix. The dosage of the water reducing admixture in each suggested mix is predicted to give a flowability within the desired range. These dosages are estimated based on previous flowability tests conducted to determine what dosage of each of the new water reducing admixtures can give the desired flowability to the reference mix (please refer to the appendix for more details).

Table 3.2 Mix Group 1

Group 1 Mixes		
Mix Name	**Ingredient**	**Parts by Weight**
Mix 1-1	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	Sika Viscocrete 2100 (mL/kg of cement)	3 mL/kg of cement
	Sika control NS (% of cement)	2%
Mix 1-2	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	Sika Viscocrete 2100 (mL/kg of cement)	3 mL/kg of cement
	Sika control NS (% of cement)	4%
Mix 1-3	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	Sika Viscocrete 2100 (mL/kg of cement)	4 mL/kg of cement
	Sika control NS (% of cement)	6%
Mix 1-4	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	Sika Viscocrete 2100 (mL/kg of cement)	5 mL/kg of cement
	Sika control NS (% of cement)	8%

Table 3.3 Mix Group 2

Group 2 Mixes		
Mix Name	**Ingredient**	**Parts by Weight**
Mix 2-1	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	BASF MasterGlenium 7620	2 mL/1 kg of cement
	MasterLife CRA 007	1 mL/1kg of cement
Mix 2-2	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	BASF MasterGlenium 7620	2 mL/1 kg of cement
	MasterLife CRA 007	2 mL/1kg of cement
Mix 2-3	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	BASF MasterGlenium 7620	2 mL/1 kg of cement
	MasterLife CRA 007	6 mL/1kg of cement
Mix 2-4	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	BASF MasterGlenium 7620	1 mL/1 kg of cement
	MasterLife CRA 007	8 mL/1kg of cement

Table 3.4 Mix Group 3

Group 3 Mixes		
Mix Name	**Ingredient**	**Parts by Weight**
Mix 3-1	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	BASF MasterGlenium 7620	2 mL/1 kg of cement
	MasterLife SRA 035	2.5ml/1kg of cement
Mix 3-2	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	BASF MasterGlenium 7620	1 mL/1 kg of cement
	MasterLife SRA 035	5 mL/1kg of cement
Mix 3-3	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	BASF MasterGlenium 7620	1 mL/1 kg of cement
	MasterLife SRA 035	7.5 mL/1kg of cement
Mix 3-4	Cement	1
	Sand/Cement ratio	1.18
	Water/(cement + micro silica) ratio	0.32
	Micro-Silica (% of cement)	7%
	BASF MasterGlenium 7620	1 mL/1 kg of cement
	MasterLife SRA 035	10 mL/1kg of cement

3.4 Mix Preparation

The mix preparation method used in this research is the method followed by the cement mortar lining company sponsoring this research. This method is part of the cement mortar lining specification used in Saudi Arabia (M03).

Using a mixer that conforms to the ASTM C109 standard method, the sand, micro-silica and 30% of the water amount is mixed together for 2 minutes. After this, the cement is added and mixed with the previous ingredients for 2 more minutes. Finally, the admixtures and the rest of the water is added and mixed with all of the other ingredients for 3 additional minutes (ILF 2015).

3.5 Properties of the Fresh and Hardened Mixes

The properties of the reference mix as well as the mixes in the three groups are studied in two testing phases:

3.5.1 Testing Phase I: Fresh Mix Properties

The first phase tests the flowability of the reference mix and mixes in the three groups using the Standard Test Method for Flow of Hydraulic Cement Mortar (ASTM C1437). The purpose of this round is to ensure that the flowability of each of the proposed mixes in the three groups fall within the range recommended for the reference mix. The flowability of the mix must be adequate so that the mortar can be properly applied with lining equipment (ILF 2015). The flowability desired for cement mortar lining mix is between 55.1% and 66.6%. This range was determined by the cement mortar lining company sponsoring this research. If the flowability of any of the mixes does not meet the desired flowability limits, the dosage of the water reducing admixture used in that mix shall be modified and the test should be repeated.

3.5.2 Testing Phase II: Hardened Mix Properties

The second phase tests focus on the drying shrinkage, compressive strength, and bending strength properties of the mixes. This testing phase can only be started when flowability of the mixes is found to satisfy desired flowability range. The drying shrinkage of the reference mix and mixes in mix groups 1, 2, and 3 are first tested. Upon determining the air-drying shrinkage of each mix, the reference mix and the two mixes that demonstrate the lowest air-drying shrinkage from each mix group are tested for bending and compressive strength.

Chapter 4: RESULTS

In this chapter, results of flowability, drying shrinkage, compressive strength, and flexural bending strength tests are given. The results will be presented by testing phase and by the order these tests were conducted.

4.1 Phase I: Properties of The Fresh Mix

4.1.1 Flowability

In this study, the flowability of mixes is measured using the ASTM C1437 standard test method for flow of hydraulic cement mortar. In addition, the AWWA guidelines and the specification used in Saudi Arabia for cement mortar lining were taken into consideration in the mix preparation process. Table 4.1 shows the flowability of the mixes.

Table 4.1 Flowability of the reference mix and mix group1, 2, and 3

Mix Name	Flowability (%)
The Reference Mix	
The Reference Mix	59.0%
Group 1 Mixes	
Mix 1-1	61.4%
Mix 1-2	58.3%
Mix 1-3	60.5%
Mix 1-4	57.3%
Group 2 Mixes	
Mix 2-1	58.7%
Mix 2-2	65.9%
Mix 2-3	61.3%
Mix 2-4	66.6%

Group 3 Mixes	
Mix 3-1	66.7%
Mix 3-2	56.7%
Mix 3-3	60.4%
Mix 3-4	55.1%

4.2 Phase II: Properties of the Hardened Mix

4.2.1 Air Drying Shrinkage

The amount of air-drying shrinkage for each mix was measured using the ASTM C596 standard for drying shrinkage of mortar containing hydraulic cement. The drying shrinkage of the reference mix was tested twice to ensure the accuracy of obtained results as the reference mix is the benchmark of evaluating the effects of adding shrinkage reducing admixtures on cement mortar lining mix. Table 4.2, Table 4.3, and Figure 4.1 show the change in drying shrinkage of the reference mix with time. In each shrinkage test conducted on the reference mix, four specimens were tested to determine the average drying shrinkage at the air-drying age of 4, 11, 18 and 25 days. While the two tests yielded slightly different average length change, the difference is considered insignificant and the average length change of the two tests is used to represent the average shrinkage of the reference mix. Some minor inaccuracy in measuring the ratios of and dosages of mixing ingredients is a potential reason for the differences found in the results.

Table 4.2 Air-Drying Shrinkage of the Reference Mix – Test 1

Mix Name	Drying Age	Specimen Number	Initial Reference Reading (mm)	Initial Reading (mm)	Age Reference Reading (mm)	Age Reading (mm)	Length Change (%)	Avg. Length Change (%)
Reference Mix - Test 1	4 Days	1	2.898	2.816	2.902	2.542	-0.111	-0.111
		2	2.898	2.786	2.902	2.516	-0.110	
		3	2.898	2.870	2.902	2.594	-0.112	
		4	2.898	2.820	2.902	2.544	-0.112	
	11 Days	1	2.898	2.816	2.920	2.496	-0.137	-0.136
		2	2.898	2.786	2.920	2.472	-0.134	
		3	2.898	2.870	2.920	2.544	-0.139	
		4	2.898	2.820	2.920	2.504	-0.135	
	18 Days	1	2.898	2.816	2.918	2.456	-0.152	-0.152
		2	2.898	2.786	2.918	2.430	-0.150	
		3	2.898	2.870	2.918	2.512	-0.151	
		4	2.898	2.820	2.918	2.456	-0.154	
	25 Days	1	2.898	2.816	2.920	2.432	-0.162	-0.162
		2	2.898	2.786	2.920	2.410	-0.159	
		3	2.898	2.870	2.920	2.484	-0.163	
		4	2.898	2.820	2.920	2.438	-0.162	

Table 4.3 Air-Drying Shrinkage of the Reference Mix – Test 2

Mix Name	Drying Age	Specimen Number	Initial Reference Reading (mm)	Initial Reading (mm)	Age Reference Reading (mm)	Age Reading (mm)	Length Change (%)	Avg. Length Change (%)
Reference Mix - Test 2	4 Days	5	2.918	3.012	2.920	2.788	-0.090	-0.091
		6	2.918	3.022	2.920	2.796	-0.091	
		7	2.918	2.956	2.920	2.730	-0.091	
		8	2.918	3.044	2.920	2.816	-0.092	
	11 Days	5	2.918	3.012	2.918	2.702	-0.124	-0.124
		6	2.918	3.022	2.918	2.714	-0.123	
		7	2.918	2.956	2.918	2.646	-0.124	
		8	2.918	3.044	2.918	2.734	-0.124	
	18 Da	5	2.918	3.012	2.918	2.666	-0.138	-0.138

		6	2.918	3.022	2.918	2.674	-0.139	
		7	2.918	2.956	2.918	2.608	-0.139	
		8	2.918	3.044	2.918	2.702	-0.137	
	25 Days	5	2.918	3.012	2.920	2.638	-0.150	-0.149
		6	2.918	3.022	2.920	2.654	-0.148	
		7	2.918	2.956	2.920	2.584	-0.150	
		8	2.918	3.044	2.920	2.674	-0.149	

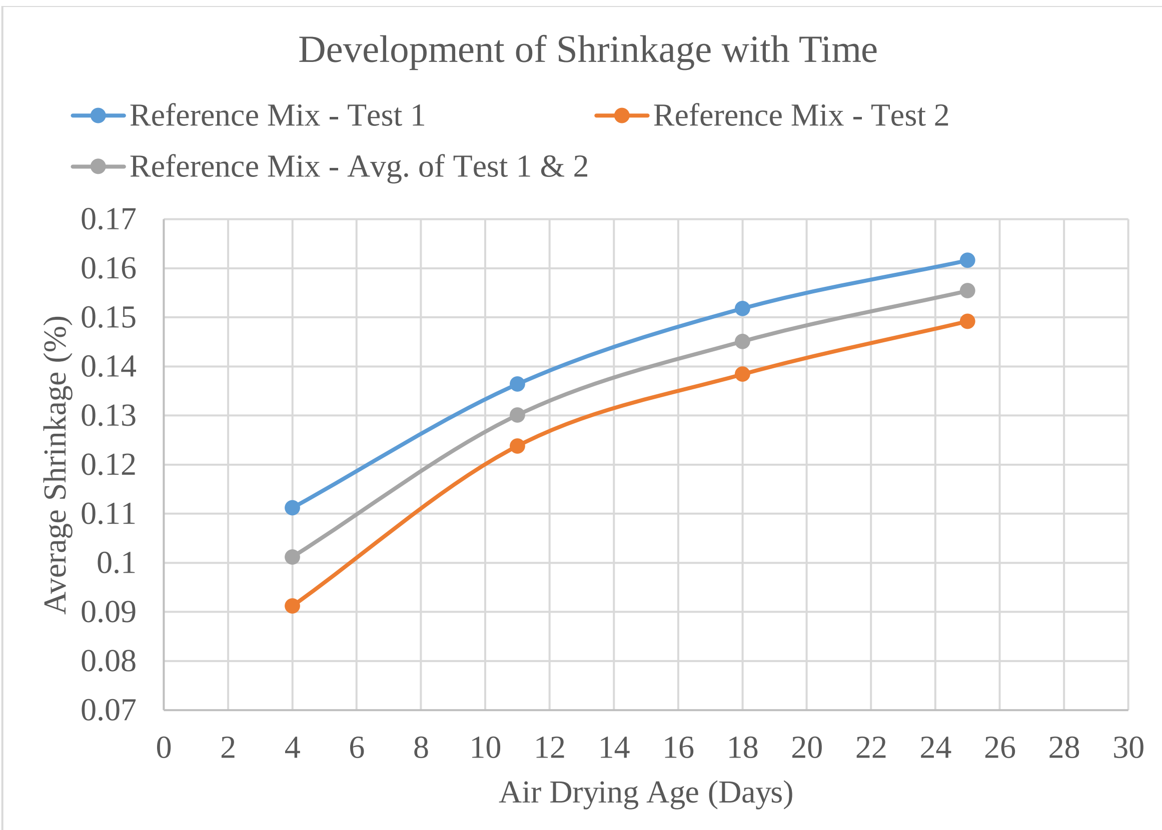


Figure 4.1 Development of Air-Drying Shrinkage with Air-Drying Age in the Reference Mix

The drying shrinkage of mixes in mix group 1 was determined using four specimens at the 4, 11, 18, and 25 air-drying age. Table 4.4 and Figure 4.2 show the change in drying shrinkage of the group 1 mixes with air-drying time.

Table 4.4 Air-Drying Shrinkage of Mix Group 1

Mix Name	Drying Age	Specimen Number	Initial Reference Reading (mm)	Initial Reading (mm)	Age Reference Reading (mm)	Age Reading (mm)	Length Change (%)	Avg. Length Change (%)
Mix 1-1	4 Day	1	2.898	2.834	2.902	2.600	-0.095	-0.100
		2	2.898	2.846	2.902	2.598	-0.101	
		3	2.898	2.660	2.902	2.412	-0.101	
		4	2.898	2.632	2.902	2.382	-0.102	
	11 Day	1	2.898	2.834	2.920	2.560	-0.118	-0.122
		2	2.898	2.846	2.920	2.564	-0.122	
		3	2.898	2.660	2.920	2.374	-0.123	
		4	2.898	2.632	2.920	2.346	-0.123	
	18 Days	1	2.898	2.834	2.918	2.516	-0.135	-0.138
		2	2.898	2.846	2.918	2.514	-0.141	
		3	2.898	2.660	2.918	2.336	-0.138	
		4	2.898	2.632	2.918	2.306	-0.138	
	25 Days	1	2.898	2.834	2.920	2.506	-0.140	-0.144
		2	2.898	2.846	2.920	2.498	-0.148	
		3	2.898	2.660	2.920	2.326	-0.142	
		4	2.898	2.632	2.920	2.292	-0.145	
Mix 1-2	4 Day	1	2.898	2.816	2.902	2.580	-0.096	-0.098
		2	2.898	2.814	2.902	2.574	-0.098	
		3	2.898	2.894	2.902	2.654	-0.098	
		4	2.898	2.864	2.902	2.620	-0.099	
	11 Day	1	2.898	2.816	2.920	2.542	-0.118	-0.119
		2	2.898	2.814	2.920	2.536	-0.120	
		3	2.898	2.894	2.920	2.618	-0.119	
		4	2.898	2.864	2.920	2.590	-0.118	
	18 Days	1	2.898	2.816	2.918	2.506	-0.132	-0.133
		2	2.898	2.814	2.918	2.500	-0.134	
		3	2.898	2.894	2.918	2.582	-0.133	
		4	2.898	2.864	2.918	2.552	-0.133	
	25 Days	1	2.898	2.816	2.920	2.490	-0.139	-0.139
		2	2.898	2.814	2.920	2.488	-0.139	
		3	2.898	2.894	2.920	2.570	-0.138	
		4	2.898	2.864	2.920	2.536	-0.140	

Mix 1-3	4 Day	1	2.902	2.638	2.918	2.432	-0.089	-0.089
		2	2.902	2.834	2.918	2.630	-0.088	
		3	2.902	2.836	2.918	2.622	-0.092	
		4	2.902	2.786	2.918	2.580	-0.089	
	11 Day	1	2.902	2.638	2.918	2.372	-0.113	-0.115
		2	2.902	2.834	2.918	2.562	-0.115	
		3	2.902	2.836	2.918	2.556	-0.118	
		4	2.902	2.786	2.918	2.516	-0.114	
	18 Days	1	2.902	2.638	2.918	2.346	-0.123	-0.124
		2	2.902	2.834	2.918	2.544	-0.122	
		3	2.902	2.836	2.918	2.534	-0.127	
		4	2.902	2.786	2.918	2.494	-0.123	
	25 Days	1	2.902	2.638	2.908	2.330	-0.126	-0.127
		2	2.902	2.834	2.908	2.526	-0.126	
		3	2.902	2.836	2.908	2.518	-0.130	
		4	2.902	2.786	2.908	2.472	-0.128	
Mix 1-4	4 Day	1	2.902	2.872	2.918	2.664	-0.090	-0.090
		2	2.902	2.590	2.918	2.384	-0.089	
		3	2.902	2.880	2.918	2.664	-0.093	
		4	2.902	2.752	2.918	2.548	-0.088	
	11 Day	1	2.902	2.872	2.918	2.602	-0.114	-0.115
		2	2.902	2.590	2.918	2.324	-0.113	
		3	2.902	2.880	2.918	2.600	-0.118	
		4	2.902	2.752	2.918	2.486	-0.113	
	18 Days	1	2.902	2.872	2.918	2.574	-0.126	-0.124
		2	2.902	2.590	2.918	2.300	-0.122	
		3	2.902	2.880	2.918	2.580	-0.126	
		4	2.902	2.752	2.918	2.460	-0.123	
	25 Days	1	2.902	2.872	2.908	2.566	-0.125	-0.126
		2	2.902	2.590	2.908	2.286	-0.124	
		3	2.902	2.880	2.908	2.562	-0.130	
		4	2.902	2.752	2.908	2.446	-0.125	

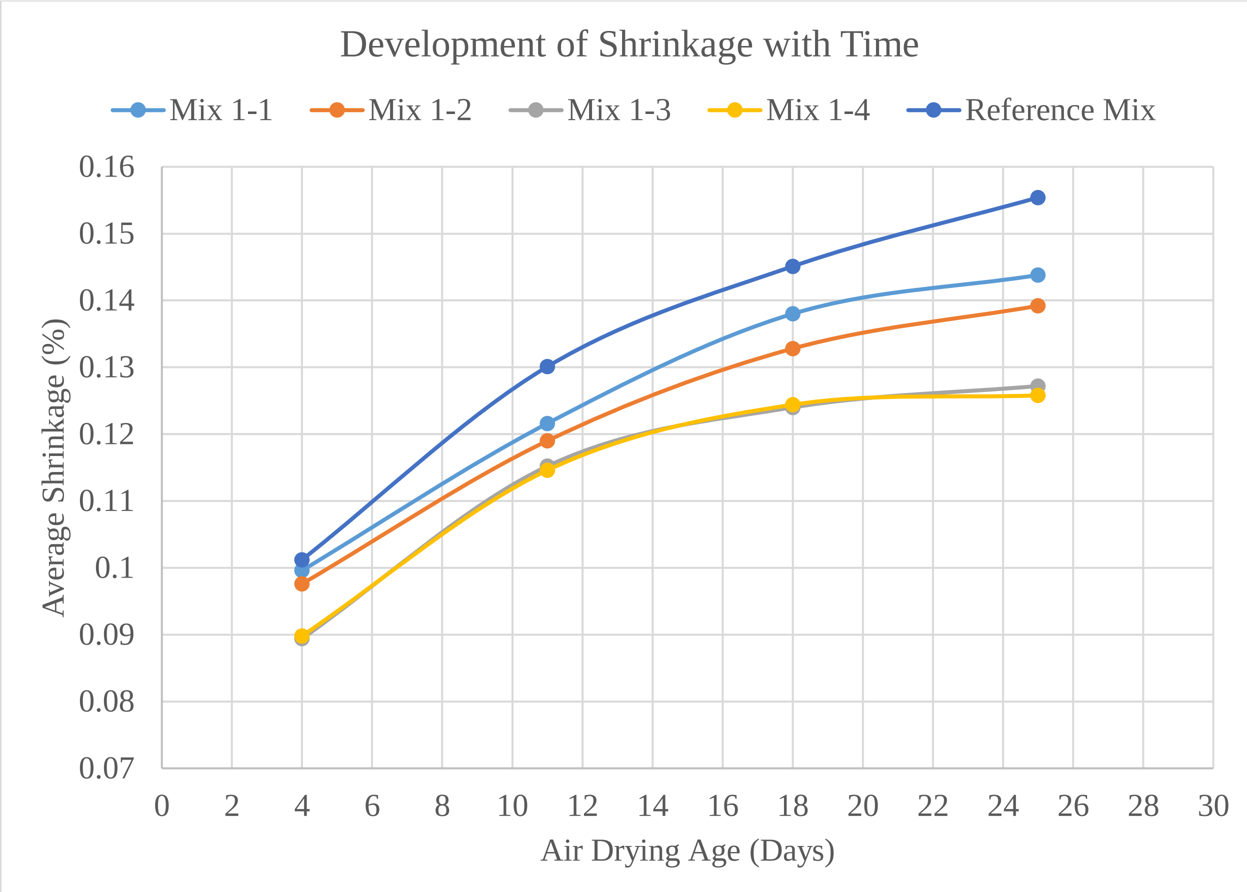


Figure 4.2 Development of Air-Drying Shrinkage with Air-Drying Age in Mix Group 1

Table 4.5 and Figure 4.3 show the change in the drying shrinkage of group 2 mixes with air-drying time. Similar to mixes in mix group 1, four specimens were used to determine the average drying shrinkage at the 4, 11, 18, and 25 air-drying age. However, the length change results obtained from specimen 2 in mix 2-4 (highlighted in red in table 4.5) were disregarded following the rules dictated by the ASTM C596 standard. According to ASTM C596, if any of the specimens has results that contradict the results obtained from majority of other specimens, the results of the specimen shall be disregarded. Specimen 2 in mix 2-4 had a positive length change (expansion) which contradicts with the results obtained from the other three specimens for the same mix. Such faulty results can be due to a technical or human error occurred while taking the initial measurements of the specimen.

Table 4.5 Air-Drying Shrinkage of Mix Group 2

Mix Name	Drying Age	Specimen Number	Initial Reference Reading (mm)	Initial Reading (mm)	Age Reference Reading (mm)	Age Reading (mm)	Length Change (%)	Avg. Length Change (%)
Mix 2-1	4 Days	1	2.918	3.048	2.920	2.838	-0.085	-0.084
		2	2.918	2.918	2.920	2.706	-0.086	
		3	2.918	3.062	2.920	2.862	-0.081	
		4	2.918	3.130	2.920	2.922	-0.084	
	11 Days	1	2.918	3.048	2.918	2.758	-0.116	-0.117
		2	2.918	2.918	2.918	2.620	-0.119	
		3	2.918	3.062	2.918	2.772	-0.116	
		4	2.918	3.130	2.918	2.842	-0.115	
	18 Days	1	2.918	3.048	2.918	2.724	-0.130	-0.131
		2	2.918	2.918	2.918	2.584	-0.134	
		3	2.918	3.062	2.918	2.734	-0.131	
		4	2.918	3.130	2.918	2.804	-0.130	
	25 Days	1	2.918	3.048	2.920	2.700	-0.140	-0.141
		2	2.918	2.918	2.920	2.564	-0.142	
		3	2.918	3.062	2.920	2.714	-0.140	
		4	2.918	3.130	2.920	2.778	-0.142	
Mix 2-2	4 Days	1	2.918	2.880	2.920	2.678	-0.082	-0.081
		2	2.918	2.946	2.920	2.742	-0.082	
		3	2.918	2.776	2.920	2.580	-0.079	
		4	2.918	2.760	2.920	2.560	-0.081	
	11 Days	1	2.918	2.880	2.918	2.598	-0.113	-0.112
		2	2.918	2.946	2.918	2.666	-0.112	
		3	2.918	2.776	2.918	2.496	-0.112	
		4	2.918	2.760	2.918	2.484	-0.110	
	18 Days	1	2.918	2.880	2.918	2.566	-0.126	-0.124
		2	2.918	2.946	2.918	2.636	-0.124	
		3	2.918	2.776	2.918	2.468	-0.123	
		4	2.918	2.760	2.918	2.450	-0.124	
	25 Days	1	2.918	2.880	2.920	2.546	-0.134	-0.133
		2	2.918	2.946	2.920	2.616	-0.133	
		3	2.918	2.776	2.920	2.448	-0.132	

		4	2.918	2.760	2.920	2.432	-0.132	
Mix 2-3	4 Days	1	2.918	2.798	2.920	2.618	-0.073	-0.073
		2	2.918	2.772	2.920	2.582	-0.077	
		3	2.918	2.882	2.920	2.702	-0.073	
		4	2.918	2.918	2.920	2.742	-0.071	
	11 Days	1	2.918	2.798	2.918	2.534	-0.106	-0.101
		2	2.918	2.772	2.918	2.512	-0.104	
		3	2.918	2.882	2.918	2.636	-0.098	
		4	2.918	2.918	2.918	2.676	-0.097	
	18 Days	1	2.918	2.798	2.918	2.508	-0.116	-0.111
		2	2.918	2.772	2.918	2.488	-0.114	
		3	2.918	2.882	2.918	2.608	-0.110	
		4	2.918	2.918	2.918	2.656	-0.105	
	25 Days	1	2.918	2.798	2.920	2.494	-0.122	-0.119
		2	2.918	2.772	2.920	2.466	-0.123	
		3	2.918	2.882	2.920	2.592	-0.117	
		4	2.918	2.918	2.920	2.640	-0.112	
Mix 2-4	4 Days	1	2.918	3.392	2.922	3.214	-0.073	-0.074
		2	2.918	2.240	2.922	3.060	0.326	
		3	2.918	2.798	2.922	2.616	-0.074	
		4	2.918	2.808	2.922	2.626	-0.074	
	11 Days	1	2.918	3.392	2.926	3.154	-0.098	-0.099
		2	2.918	2.240	2.926	3.998	0.700	
		3	2.918	2.798	2.926	2.556	-0.100	
		4	2.918	2.808	2.926	2.566	-0.100	
	18 Days	1	2.918	3.392	2.914	3.126	-0.105	-0.107
		2	2.918	2.240	2.914	2.974	0.295	
		3	2.918	2.798	2.914	2.526	-0.107	
		4	2.918	2.808	2.914	2.534	-0.108	
	25 Days	1	2.918	3.392	2.922	3.118	-0.111	-0.113
		2	2.918	2.240	2.922	2.966	0.289	
		3	2.918	2.798	2.922	2.516	-0.114	
		4	2.918	2.808	2.922	2.528	-0.114	

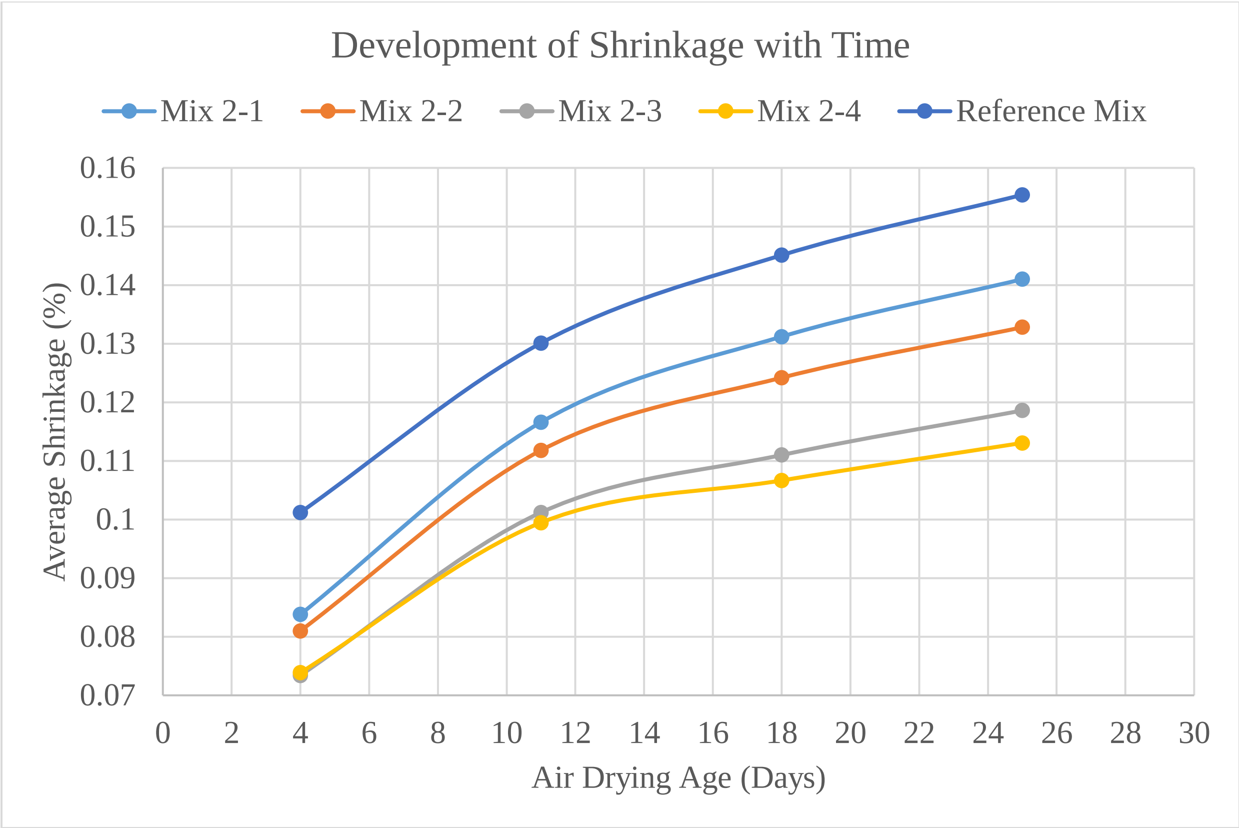


Figure 4.3 Development of Air-Drying Shrinkage with Air-Drying Age in Mix Group 2

Table 4.6 and Figure 4.4 show the change in the shrinkage of the specimens in group 3 with air-drying time. While the average drying shrinkage of mix 1, 3, and 4 in group 3 were determined using four specimens for each mix, the average drying shrinkage of mix 3-2 was determined using only two specimens. One of the mix's specimens was damaged during the curing process and the results obtained for the other specimen (specimen 3) were disregarded. The results obtained from specimen 3 in mix 3-2 indicates that a positive length change (expansion) occurred in the specimen; this contradicts the rest of the results obtained from the other two specimens for the same mix. As mentioned earlier, a potential reason for such faulty results is usually due to technical or human error occurs while taking the initial measurements of the specimen.

Table 4.6 Air-Drying Shrinkage of Mix Group 3

Mix Name	Drying Age	Specimen Number	Initial Reference Reading (mm)	Initial Reading (mm)	Age Reference Reading (mm)	Age Reading (mm)	Length Change (%)	Avg. Length Change (%)
Mix 3-1	4 Days	1	2.918	2.798	2.918	2.532	-0.106	-0.107
		2	2.918	2.780	2.918	2.512	-0.107	
		3	2.918	2.738	2.918	2.470	-0.107	
		4	2.918	2.782	2.918	2.518	-0.106	
	11 Days	1	2.918	2.798	2.914	2.498	-0.118	-0.118
		2	2.918	2.780	2.914	2.484	-0.117	
		3	2.918	2.738	2.914	2.438	-0.118	
		4	2.918	2.782	2.914	2.486	-0.117	
	18 Days	1	2.918	2.798	2.920	2.470	-0.132	-0.132
		2	2.918	2.780	2.920	2.450	-0.133	
		3	2.918	2.738	2.920	2.410	-0.132	
		4	2.918	2.782	2.920	2.458	-0.130	
	25 Days	1	2.918	2.798	2.922	2.460	-0.137	-0.136
		2	2.918	2.780	2.922	2.446	-0.135	
		3	2.918	2.738	2.922	2.396	-0.138	
		4	2.918	2.782	2.922	2.452	-0.134	
Mix 3-2	4 Days	1	2.918	2.672	2.918	2.430	-0.097	-0.097
		2	2.918	2.654	2.918	2.412	-0.097	
		3	2.918	2.152	2.918	2.417	0.106	
	11 Days	1	2.918	2.672	2.914	2.402	-0.106	-0.106
		2	2.918	2.654	2.914	2.386	-0.106	
		3	2.918	2.152	2.914	2.886	0.295	
	18 Days	1	2.918	2.672	2.920	2.376	-0.119	-0.118
		2	2.918	2.654	2.920	2.362	-0.118	
		3	2.918	2.152	2.920	2.862	0.283	
	25 Days	1	2.918	2.672	2.922	2.376	-0.120	-0.121
		2	2.918	2.654	2.922	2.354	-0.122	
		3	2.918	2.152	2.922	2.862	0.282	
Mix 3-3	4 Days	1	2.914	3.168	2.918	2.950	-0.089	-0.092
		2	2.914	3.102	2.918	2.874	-0.093	

		3	2.914	2.894	2.918	2.654	-0.098	
		4	2.914	2.880	2.918	2.660	-0.090	
	11 Days	1	2.914	3.168	2.914	2.918	-0.100	-0.102
		2	2.914	3.102	2.914	2.852	-0.100	
		3	2.914	2.894	2.914	2.626	-0.107	
		4	2.914	2.880	2.914	2.630	-0.100	
	18 Days	1	2.914	3.168	2.920	2.892	-0.113	-0.114
		2	2.914	3.102	2.920	2.826	-0.113	
		3	2.914	2.894	2.920	2.606	-0.118	
		4	2.914	2.880	2.920	2.608	-0.111	
	25 Days	1	2.914	3.168	2.922	2.884	-0.117	-0.117
		2	2.914	3.102	2.922	2.818	-0.117	
		3	2.914	2.894	2.922	2.594	-0.123	
		4	2.914	2.880	2.922	2.608	-0.112	
Mix 3-4	4 Days	1	2.918	2.790	2.918	2.578	-0.085	-0.086
		2	2.918	2.744	2.918	2.526	-0.087	
		3	2.918	2.766	2.918	2.550	-0.086	
		4	2.918	2.768	2.918	2.552	-0.086	
	11 Days	1	2.918	2.790	2.914	2.550	-0.094	-0.096
		2	2.918	2.744	2.914	2.498	-0.097	
		3	2.918	2.766	2.914	2.514	-0.099	
		4	2.918	2.768	2.914	2.526	-0.095	
	18 Days	1	2.918	2.790	2.920	2.528	-0.106	-0.108
		2	2.918	2.744	2.920	2.472	-0.110	
		3	2.918	2.766	2.920	2.494	-0.110	
		4	2.918	2.768	2.920	2.498	-0.109	
	25 Days	1	2.918	2.790	2.922	2.524	-0.108	-0.110
		2	2.918	2.744	2.922	2.468	-0.112	
		3	2.918	2.766	2.922	2.494	-0.110	
		4	2.918	2.768	2.922	2.496	-0.110	

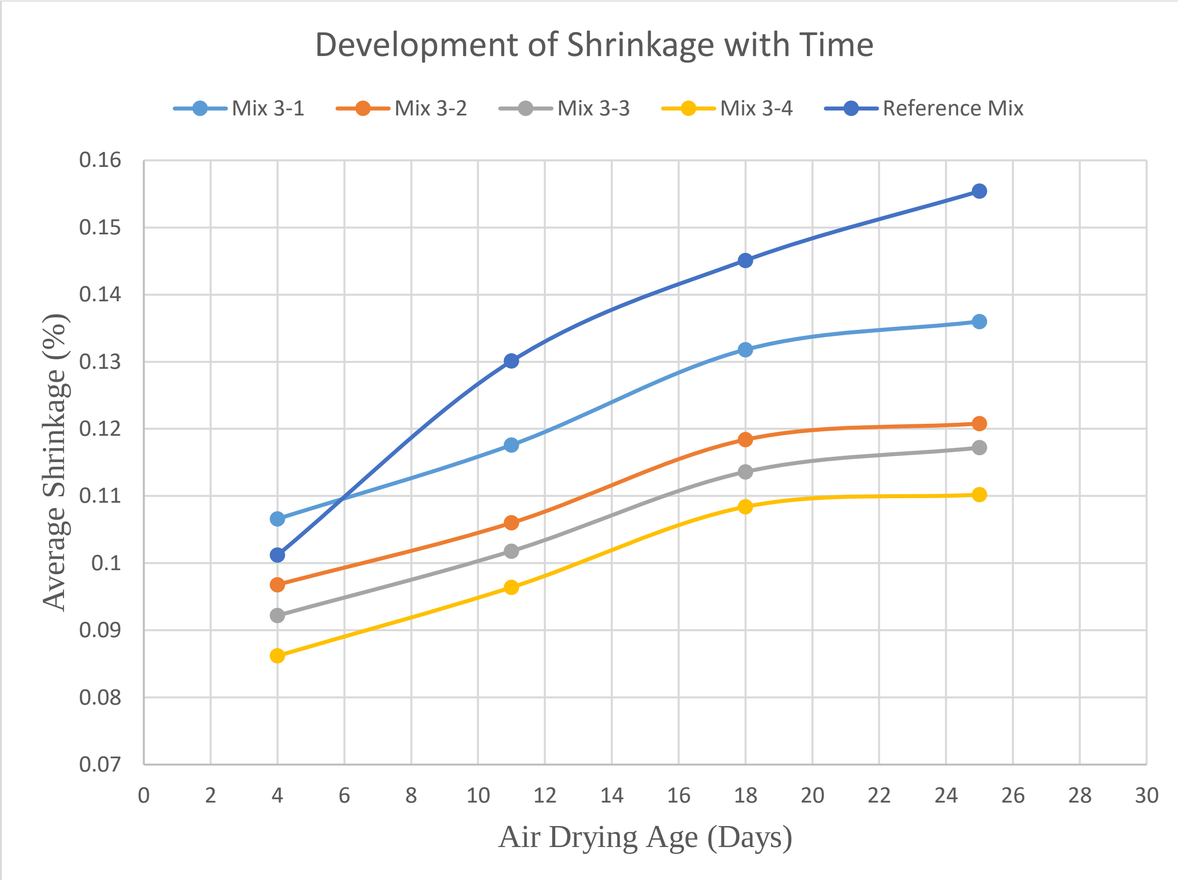


Figure 4.4 Development of Air-Drying Shrinkage with Air-Drying Age in Mix Group 3

4.2.2 Compressive Strength

In this research, compressive strength is measured using the ASTM C109 standard test method for compressive strength of hydraulic cement mortars. The compressive strength of the reference mix and the two mixes that have the lowest air-drying shrinkage in each mix group were tested. The compressive strength of each mix was measured at the age of 14 and 28 days from casting.

The compressive strength of the reference mix was measured by using three specimens at each age. Table 4.7 shows the compressive strength of the reference mix at the age of 14 and 28 days.

Table 4.7 Compressive Strength of the Reference Mix

Mix Name	Specimen Age	Specimen Number	Compressive Strength (MPa)	Avg. Compressive Strength (MPa)
Reference Mix	14 Days	1	82.39	79.04
		2	75.65	
		3	79.07	
	28 Days	1	79.75	86.98
		2	97.93	
		3	83.26	

As mix 3 and 4 in mix group 1 have the lowest drying shrinkage values, the compressive strength of these two mixes were tested at the age of 14 and 28 days. However, the 14-day compressive strength results of mix 4 were lost due to a technical glitch in the testing equipment. Table 4.8 shows the compressive strength of mix 1-3 at the age of 14 and 28 days and mix 1-4 at the age of 28 days.

Table 4.8 Compressive Strength of Mix 1-3 and 1-4

Mix Name	Specimen Age	Specimen Number	Compressive Strength (MPa)	Avg. Compressive Strength (MPa)
Mix 1-3	14 Days	1	70.74	73.91
		2	73.64	
		3	77.36	
	28 Days	1	87.12	82.04
		2	78.94	

		3	80.07	
Mix 1-4	14 Days	-		
	28 Days	1	74.66	74.27
		2	75.04	
		3	73.11	

The compressive strength of mix 3 and mix 4 in the mix group 2 were tested at the age of 14 and 28 days as they have the lowest air-drying shrinkage in the group. Table 4.9 shows the compressive strength of Mix 2-3 and 2-4 at the age of 14 and 28 days.

Table 4.9 Compressive Strength of Mix 2-3 and 2-4

Mix Name	Specimen Age	Specimen Number	Compressive Strength (MPa)	Avg. Compressive Strength (MPa)
Mix 2-3	14 Days	1	70.26	70.78
		2	74.89	
		3	67.2	
	28 Days	1	68.71	74.25
		2	72.72	
		3	81.32	
Mix 2-4	14 Days	1	72.26	67.19
		2	52.27	
		3	77.04	

	28 Days	1	76.49	72.94
		2	77.52	
		3	64.8	

Similar to mix group 2, the compressive strength of mix 3 and mix 4 in the mix group 3 were tested at the age of 14 and 28 days as they have the lowest air-drying shrinkage in the group. Table 4.10 shows the compressive strength of Mix 2-3 and 2-4 at the age of 14 and 28 days.

Table 4.10 Compressive Strength of Mix 3-3 and 3-4

Mix Name	**Specimen Age**	**Specimen Number**	**Compressive Strength (MPa)**	**Avg. Compressive Strength (MPa)**
Mix 3-3	14 Days	1	67.56	72.09
		2	75.93	
		3	72.77	
	28 Days	1	78.2	78.31
		2	78.4	
		3	78.32	
Mix 3-4	14 Days	1	82.26	80.43
		2	79.25	
		3	79.78	
	28 Days	1	84.11	82.17
		2	86.07	
		3	76.32	

4.2.3 Bending Strength

The flexural bending strength of the reference mix and the two mixes that have the lowest drying shrinkage in each mix group were measured using the DIN 1164-7 standard. The ultimate bending strength of each mix was measured using the average of 3 specimens at the age of 28 days from casting.

Table 4.11 shows the flexural bending strength of the reference mix at the age of 28 days. The bending strength of specimen 1 of the reference mix was lost due to a technical glitch in the testing machine.

Table 4.11 Bending Strength of the Reference Mix

Mix Name	Specimen Age	Specimen Number	Bending Strength (MPa)	Avg. Bending Strength (MPa)
Reference Mix	28 Days	1	-	6.37
		2	6.04	
		3	6.7	

The bending strength of mix 3 and 4 in each mix group was tested as these two mixes have the lowest drying shrinkage values in each group. Table 4.12, 4.13, and 4.14 show the bending strength mix 3 and 4 in mix group 1, 2, and 3 respectively at the age of 28 days.

Table 4.12 Bending Strength of Mix 1-3 and 1-4

Mix Name	Specimen Age	Specimen Number	Bending Strength (MPa)	Avg. Bending Strength (MPa)
Mix 1-3	28 Days	1	6.94	7.43
		2	7.62	
		3	7.72	
Mix 1-4	28 Days	1	7.25	7.13
		2	6.81	
		3	7.32	

Table 4.13 Bending Strength of Mix 2-3 and 2-4

Mix Name	Specimen Age	Specimen Number	Bending Strength (MPa)	Avg. Bending Strength (MPa)
Mix 2-3	28 Days	1	6.59	6.76
		2	6.68	
		3	7	
Mix 2-4	28 Days	1	6.92	6.58
		2	6.59	
		3	6.23	

Table 4.14 Bending Strength of Mix 3-3 and 3-4

Mix Name	Specimen Age	Specimen Number	Bending Strength (MPa)	Avg. Bending Strength (MPa)
Mix 3-3	28 Days	1	7.16	6.77
		2	6.81	
		3	6.33	
Mix 3-4	28 Days	1	6.97	6.73
		2	6.22	
		3	6.99	

Chapter 5: DISCUSSION

As previously discussed in the literature review, ingredients and ratios of cement mortar mix affect the characteristics of fresh and hardened cement mortar lining. Therefore, studying the effects of a single cement mortar ingredient requires fixing the other ingredients and ratios in the mix. Results obtained in this study show that shrinkage reducing admixtures have a significant positive impact on the shrinkage of cement mortar lining. However, different types and dosages of shrinkage reducing admixtures affect shrinkage differently. Figures 5.1, 5.2, and 5.3 show the impact of different dosages of the shrinkage reducing admixtures used in this research on the shrinkage of tested mixes at the air-drying age of 25 days. Each point in the figures represents the average shrinkage reduction caused by adding shrinkage reducing admixture at a certain dosage. As it is assumed that replacing the water reducing admixture in the original mix does not affect shrinkage as it gives flowability within the desired range, the origin point of each graph is assumed to be for the reference mix when there is no shrinkage reducing admixture added to the mix. While interpreting Figures 5.1 – 5.3, possible differences in the mix designs in addition to the dosage of shrinkage reducing admixtures (e.g., differences in the type of water reducing admixture used and differences in dosages of water reducing admixtures used) should be kept in mind. Mix designs given in Tables 3.1 – 3.4 should be taken into account while making comparisons between different dosages of shrinkage reducing admixtures used in this study.

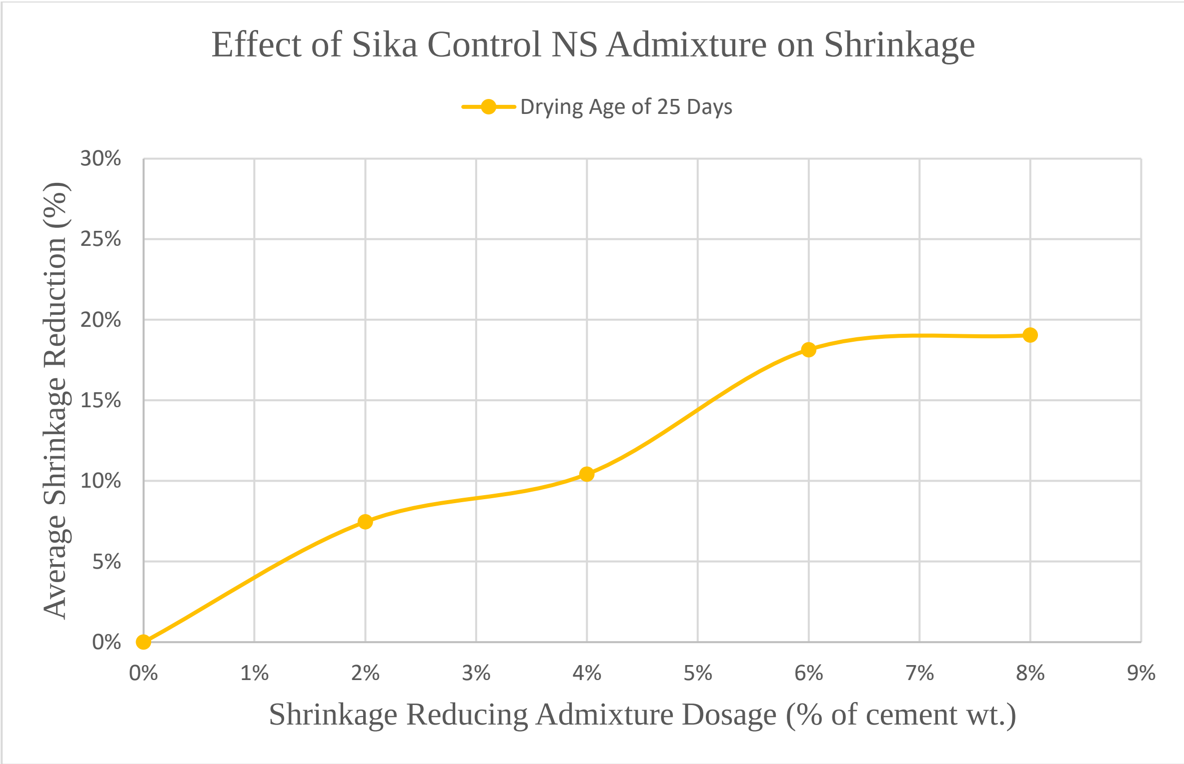


Figure 5.1 The Effect of Sika Control NS Admixture on Mix Shrinkage

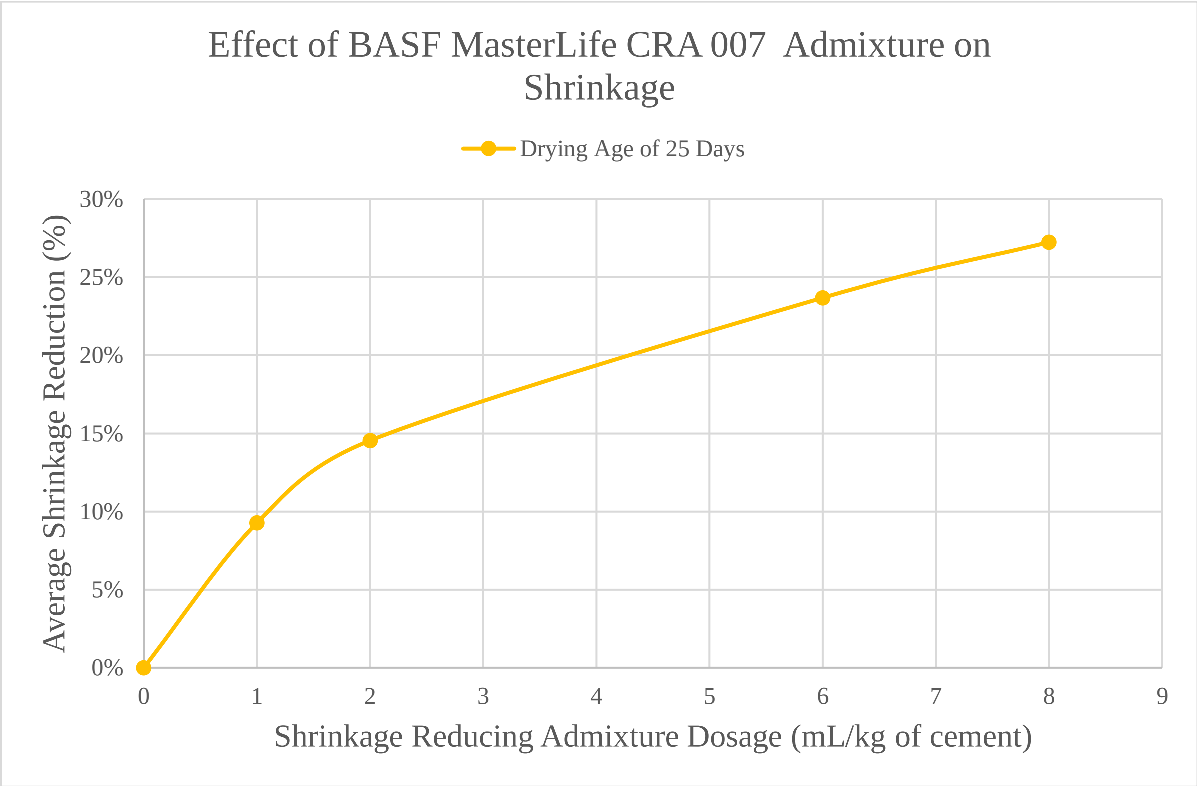


Figure 5.2 The Effect of BASF MasterLife CRA 007 Admixture on Mix Shrinkage

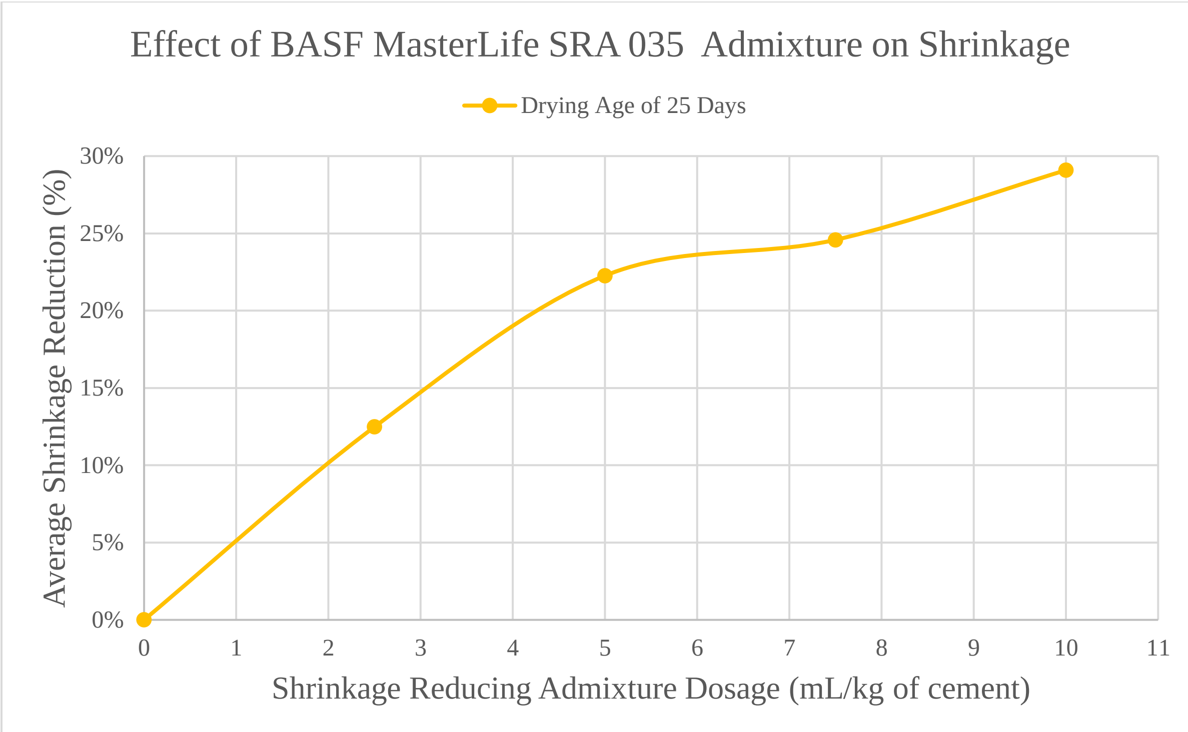


Figure 5.3 The Effect of BASF MasterLife SRA 035 Admixture on Mix Shrinkage

From the previous figures, it can be seen that using higher dosages of shrinkage reducing admixture lowers the drying shrinkage of the cement mortar lining mixes. However, the relation between the two parameters is not linear and was found to be different from one admixture to another. The highest drying shrinkage reduction achieved in this research was around 29.1%. This was achieved in mix 3-4 by using the highest dosage tested for the BASF MasterLife SRA 035 shrinkage reducing admixture. A close percentage of drying shrinkage reduction (31%) was achieved by previous research conducted on a concrete mix using different shrinkage reducing admixture (Saliba et al. 2011).

The trend of the shrinkage reduction shown in Figure 5.3 indicates that a higher dosage can result in a higher shrinkage reduction percent. In fact, all the tested shrinkage reducing admixtures have the potential to reduce shrinkage at higher levels when used at dosages higher than the dosage range suggested by the data sheets of the admixtures. These findings suggest that different shrinkage reducing admixtures should be considered during the mix-design process in order to achieve the lowest possible shrinkage in cement mortar lining. The effect of each admixture on cement mortar lining shrinkage should be studied by testing different dosages within and higher than the dosage range suggested by the admixtures' data sheets.

The compressive strength results obtained in this research show that shrinkage reducing admixtures reduce the compressive strength of cement mortar lining. Figure 5.4 shows the compressive strength of the reference mix and the mixes that contained shrinkage reducing admixtures at the age of 28 days.

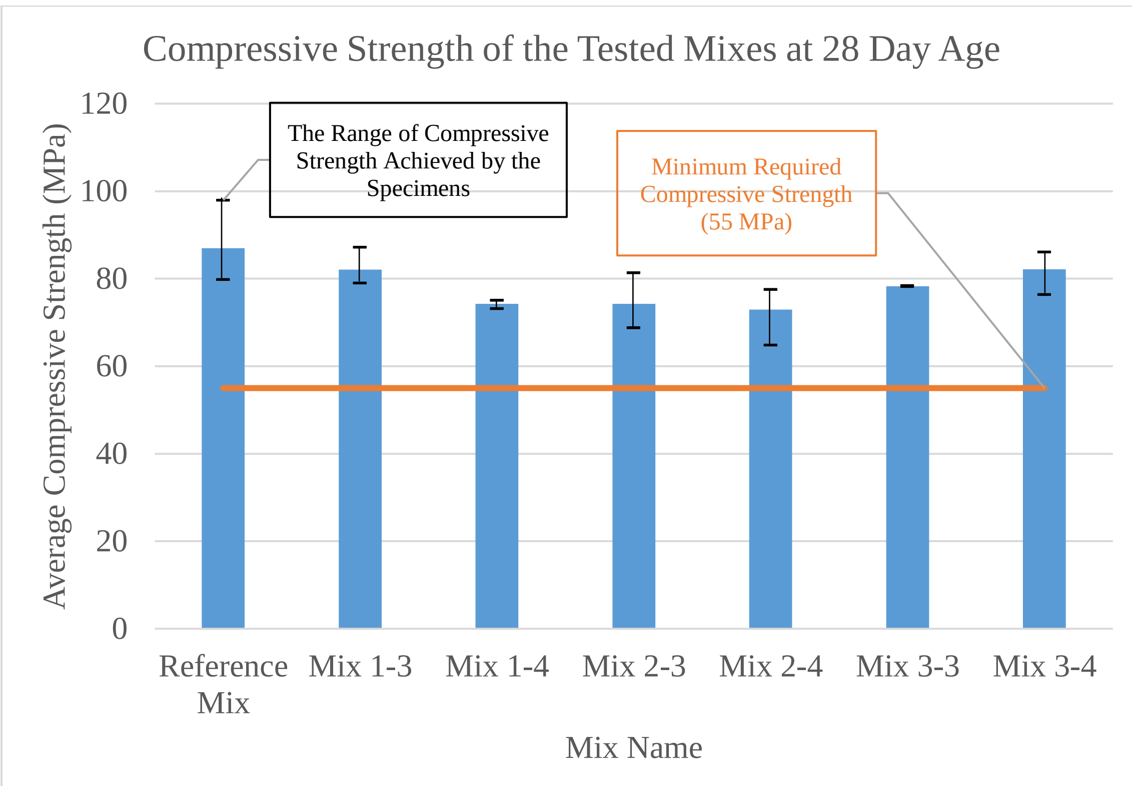


Figure 5.4 The Compressive Strength of the Tested Mixes at 28 Day Age

From Figure 5.4, it can be seen that the shrinkage reducing admixtures studied in this research reduced the compressive strength of the cement mortar lining mix by 5 to 16% (at the age of 28 days). This compressive-strength reduction range is in line with previous research conducted on a concrete mix where Saliba et al. (2011) found that shrinkage reducing admixture can cause a reduction in the compressive strength of a concrete mix by 4 to 14%. This reduction was attributed to the increase of the average pore diameter in the concrete mix, that occurs because of the shrinkage reducing admixture. The increase of the average pore diameter may cause a reduction in the cement hydration in the mix; and thereafter, a delay in the setting time of the mix and slower strength gain (Saliba et al. 2011).

While the compressive strength decrease in some mixes is relatively high, all the tested mixes satisfied the minimum compressive strength required by AWWA standards and the company that sponsors this research (31 and 55 MPa respectively). Therefore, the effect of the tested shrinkage reducing admixtures on the compressive strength of cement mortar lining is insignificant.

On the other hand, the bending strength results obtained in this study show that shrinkage reducing admixtures increased the bending strength of cement mortar lining. Figure 5.4 shows the bending strength values for the reference mix and the mixes that have shrinkage reducing admixtures at the age of 28 days.

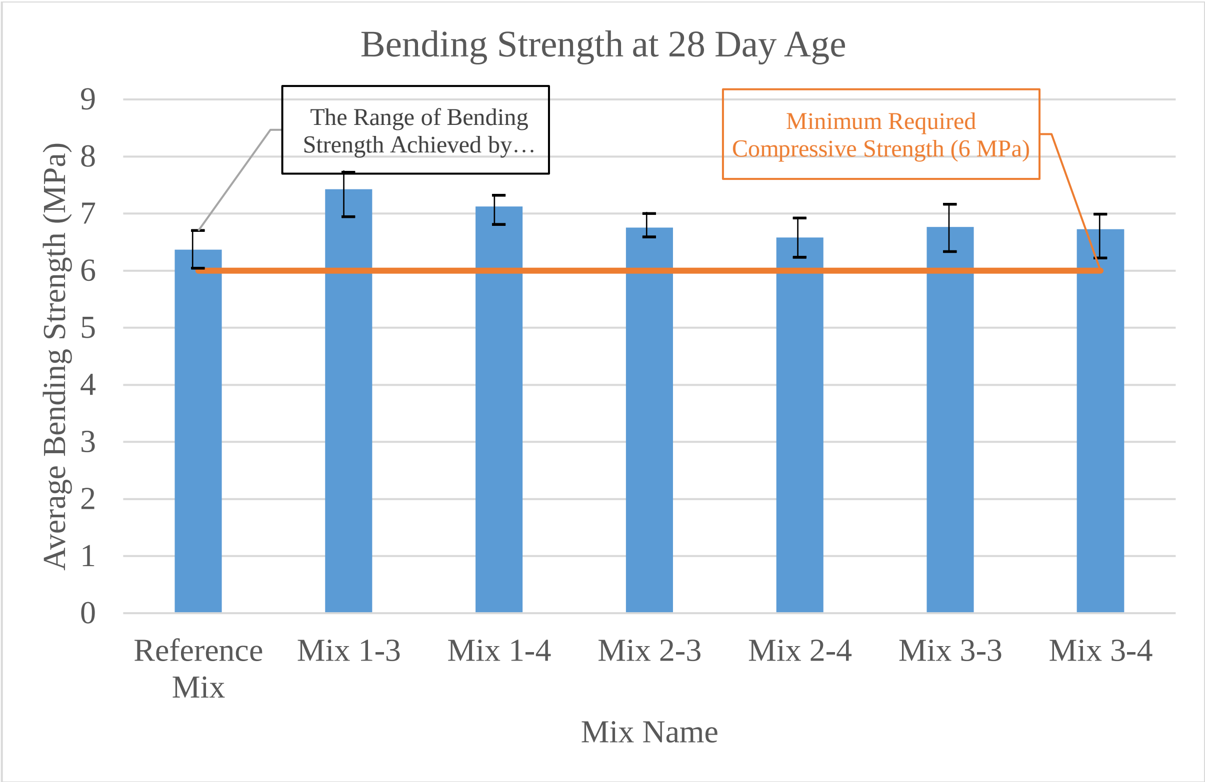


Figure 5.5 The Bending Strength of the Tested Mixes at 28 Day Age

The tested shrinkage reducing admixtures increased the bending strength of the cement mortar lining mix by 4 to 16.6%. While there is no definite reason for the bending strength increase, this increase can be attributed to the shrinkage reduction occurred due to the use of the shrinkage reducing admixtures. Reducing shrinkage in cement mortar reduces the residual tensile stress in the mix, and consequently, increases the cement mortar capacity to withstand higher tensile stresses.

Chapter 6: CONCLUSION

Shrinkage reducing admixtures are found to significantly reduce the drying shrinkage of cement mortar lining. The higher the shrinkage reducing admixture dosage, the larger the drying shrinkage decrease in cement mortar lining mix. However, the relationship between the admixture dosage and the decrease in drying shrinkage is not linear. In addition, the dosage of shrinkage reducing admixture that gives that highest possible shrinkage reduction does not necessarily fall within the dosage range recommended by the admixture data sheet. Therefore, it is recommended that multiple shrinkage reducing admixtures are studied in the mix-design process of cement mortar lining. The tested dosages for each admixture should include dosages within and outside the dosage range recommended by the admixture data sheet.

The compressive and bending strength of cement mortar lining mix is directly affected by shrinkage reducing admixture. The results suggest that shrinkage reducing admixtures negatively affect the compressive strength of a cement mortar lining mix. Depending on the type and dosage of the shrinkage reducing admixture used, the compressive strength of cement mortar lining is expected to decrease by 5 to 16%. It was also observed that while the shrinkage reducing admixtures decrease the compressive strength of cement mortar lining, the minimum required compressive strength of the lining is highly likely to be satisfied, as all the tested mixes passed the minimum required compressive strength by a large margin. This means that a higher shrinkage reducing admixtures can be used and yet still meet the minimum compressive strength requirement.

On the other hand, it was observed that shrinkage reducing admixtures have a positive impact on the bending strength of cement mortar lining. The bending strength of cement mortar lining is expected to increase by 4 to 16.6%. A potential reason for the bending strength increase is due to the decrease in the drying shrinkage of the mix by the shrinkage reducing admixture. Decreasing the drying shrinkage of cement mortar lining reduces shrinkage cracks and residual tensile stresses that develop in the hardened mix. This in turn may result in an increase in the bending strength of the hardened cement mortar mix.

The curing procedures involved submerging specimens in a water tank rather than a tank filled with lime saturated water. This procedure was adopted in order to replicate the testing procedures followed by the sponsor. Even though this may result in a deviation from curing practices dictated by standards, the results are still valid, as the reference mix and trial mixes were all cured following the same procedure. Moreover, the compressive and bending strength values for all specimens are still above the minimum threshold values, even after the specimens were cured in regular potable water rather than lime saturated water.

Finally, it is recommended that the effects of shrinkage reducing admixtures on other properties of cement mortar lining mixes are studied during the mix-design process. Such properties include water permeability and ion chloride permeability as they have a significant impact on reducing corrosion in cement mortar lined pipes as discussed in the literature review.

APPENDIX

Tables A.1 and A.2 show the Dosages of Sika Viscocrete 2100 and BASF MasterGlenium 7920 water reducing admixtures can replace the water reducing admixture in the reference mix and give the same desired flowability.

Table A.1 Sika Viscocrete 2100 Admixture Dosage that Gives the Desired flowability to the Reference Mix

Sika Viscocrete 2100			
Dosage (ml/kg of cement)	**Test Number**	**Flowability**	**Avg. Flowability**
2	Test 1	62.3	61.26
	Test 2	59.3	
	Test 3	62.2	

Table A.2 BASF MasterGlenium 7920 Admixture Dosage that Gives the Desired flowability to the Reference Mix

BASF MasterGlenium 7920			
Dosage (ml/kg of cement)	**Test Number**	**Flowability**	**Avg. Flowability**
3	Test 1	66.5	65.53
	Test 2	66.4	
	Test 3	63.7	

Test Report A.1 Compressive Strength Report – Reference Mix

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Reference Mix

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference :

Specimen type : Cube   Admixture 2 : _

Admixture 1 : Fosroc Cebex 305

Sample conditions:

Curing Time : 14 Days

Specimen ID : 1

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0   Density [Kg/m3] : 0.0   Mass [Kg] : 0.000

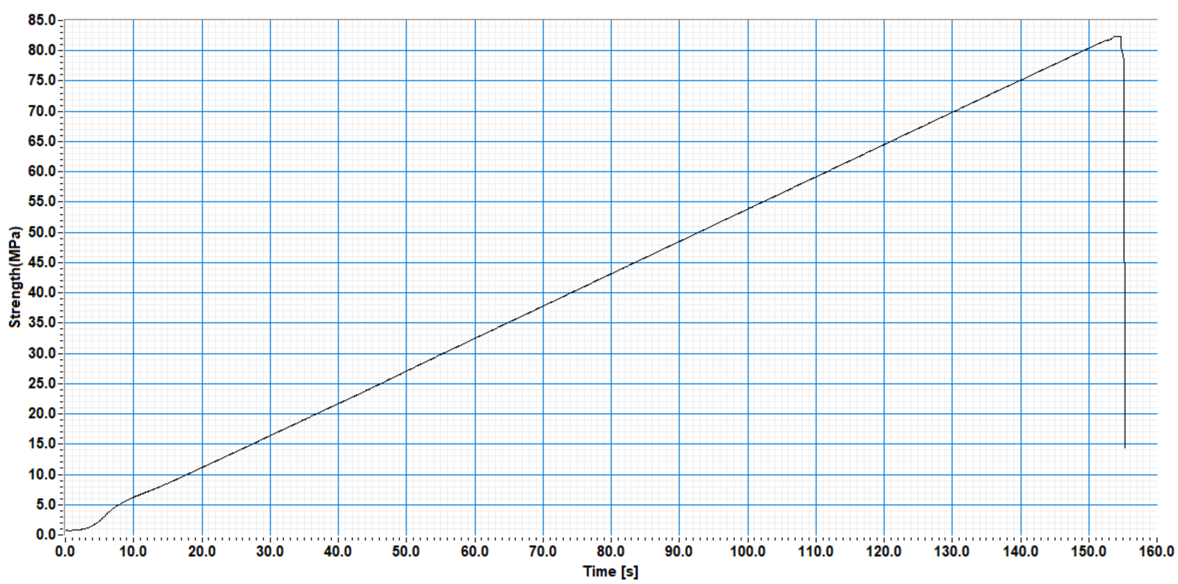
: : Specimen age [gg] : 28 days

Load Rate(N/s) : 1334.207   Test date : 02/28/20 - 21:37

Max Load [kN] : 205.98   Strength [MPa] : 82.39

Failure type

Notes :



Test Report A.2 Compressive Strength Report – Reference Mix

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Reference Mix		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: -		
Specimen type	: Cube	Admixture 2	: -
Admixture 1	: Fosroc Cebex 305		

Sample conditions:

Curing Time : 14 Days

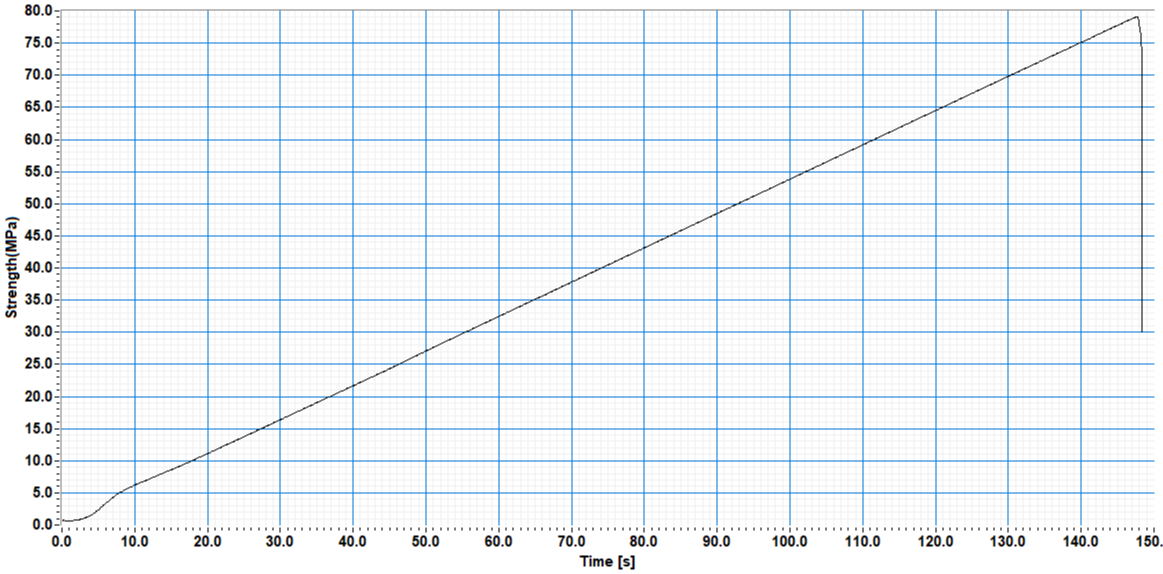
Specimen ID : 3

Dimensions	: a(mm) 50.00	b(mm) 50.00	c(mm) 50.00		
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1334.444	Test date	: 02/28/20 - 21:37		

Max Load [kN] : 197.67 **Strength [MPa] : 79.07**

Failure type

Notes :



Test Report A.3 Compressive Strength Report – Reference Mix

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Reference Mix		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	:		
Specimen type	: Cube	Admixture 2	: -
Admixture 1	: Fosroc Cebex 305		

Sample conditions:

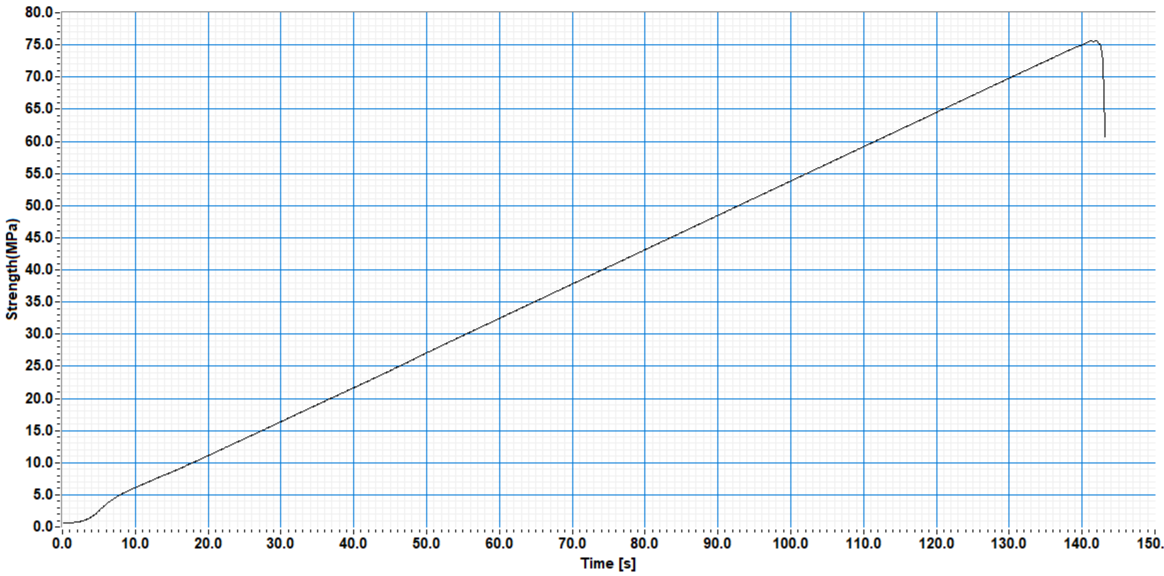
Curing Time	: 14 Days
	:
	:
Specimen ID	: 2

Dimensions	: a(mm) 50.00	b(mm) 50.00		c(mm) 50.00	
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1335.336	Test date		: 02/28/20 - 21:37	

Max Load [kN] **: 189.13** **Strength [MPa]** **: 75.65**

Failure type

Notes :



Test Report A.4 Compressive Strength Report – Reference Mix

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Reference Mix

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference :

Specimen type : Cube

Admixture 2 : -

Admixture 1 : Fosroc Cebex 305

Sample conditions:

Curing Time : 28 Days

:

:

Specimen ID : 1

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0

Density [Kg/m3] : 0.0

Mass [Kg] : 0.000

:

:

Specimen age [gg] : 28 days

Load Rate(N/s) : 1334.977

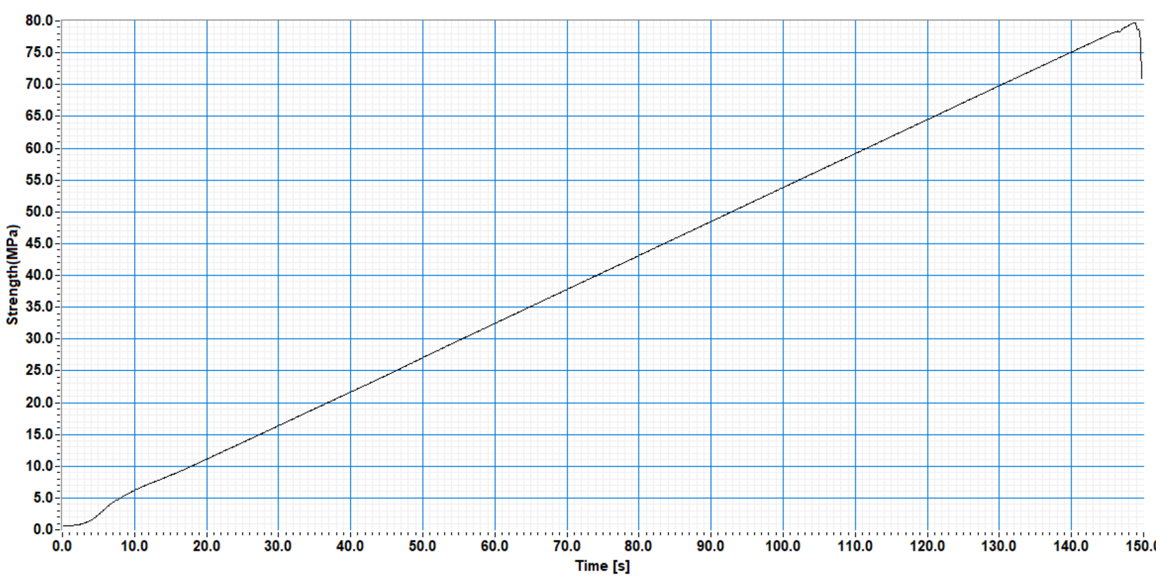
Test date : 03/18/20 - 18:07

Max Load [kN] : 199.37

Strength [MPa] : 79.75

Failure type

Notes :



Test Report A.5 Compressive Strength Report – Reference Mix

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Reference Mix		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	:		
Specimen type	: Cube	Admixture 2	: -
Admixture 1	: Fosroc Cebex 305		

Sample conditions:

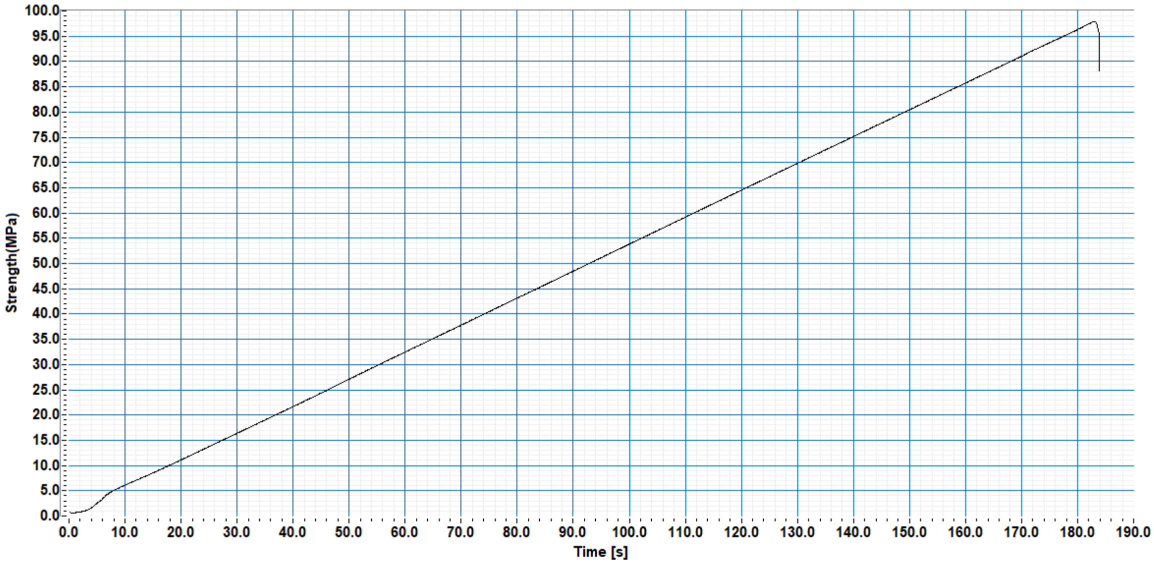
Curing Time	: 28 Days
	:
	:
Specimen ID	: 2

Dimensions	:	a(mm)	50.00	b(mm)	50.00	c(mm)	50.00
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000		
	:		:	Specimen age [gg]	: 28 days		
Load Rate(N/s)	: 1333.751	Test date	: 03/13/20 - 18:07				

Max Load [kN] **: 244.83** **Strength [MPa]** **: 97.93**

Failure type

Notes :



Test Report A.6 Compressive Strength Report – Reference Mix

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Reference Mix		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	:		
Specimen type	: Cube	Admixture 2	: -
Admixture 1	: Fosroc Cebex 305		

Sample conditions:

Curing Time : 28 Days

Specimen ID : 3

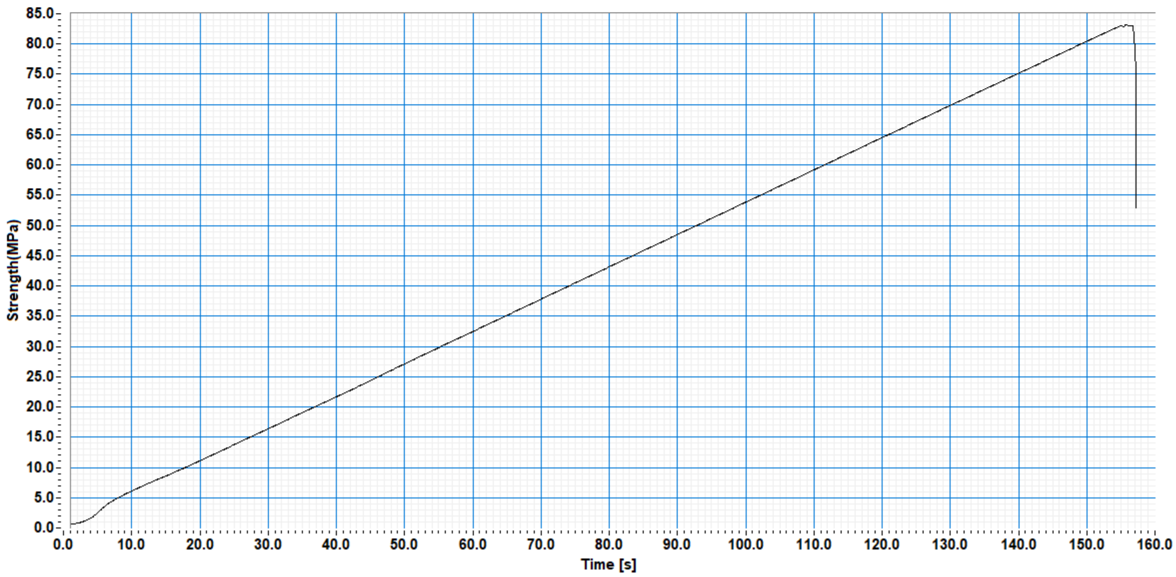
Dimensions	:	a(mm)	50.00	b(mm)	50.00	c(mm)	50.00

Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	:	0.000
	:		:	Specimen age [gg]	:	28 days
Load Rate(N/s)	: 1334.638	Test date			:	03/13/20 - 18:07

Max Load [kN] **: 208.15** **Strength [MPa]** **: 83.26**

Failure type

Notes :



Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 1-3

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 1-3

Specimen type : Cube

Admixture 2 : MasterLife SRA 035

Admixture 1 : BASF MasterGlenium 7620

Sample conditions:

Curing Time : 14 Days

Specimen ID : 1

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0

Density [Kg/m3] : 0.0

Mass [Kg] : 0.000

:

:

Specimen age [gg] : 28 days

Load Rate(N/s) : 1335.701

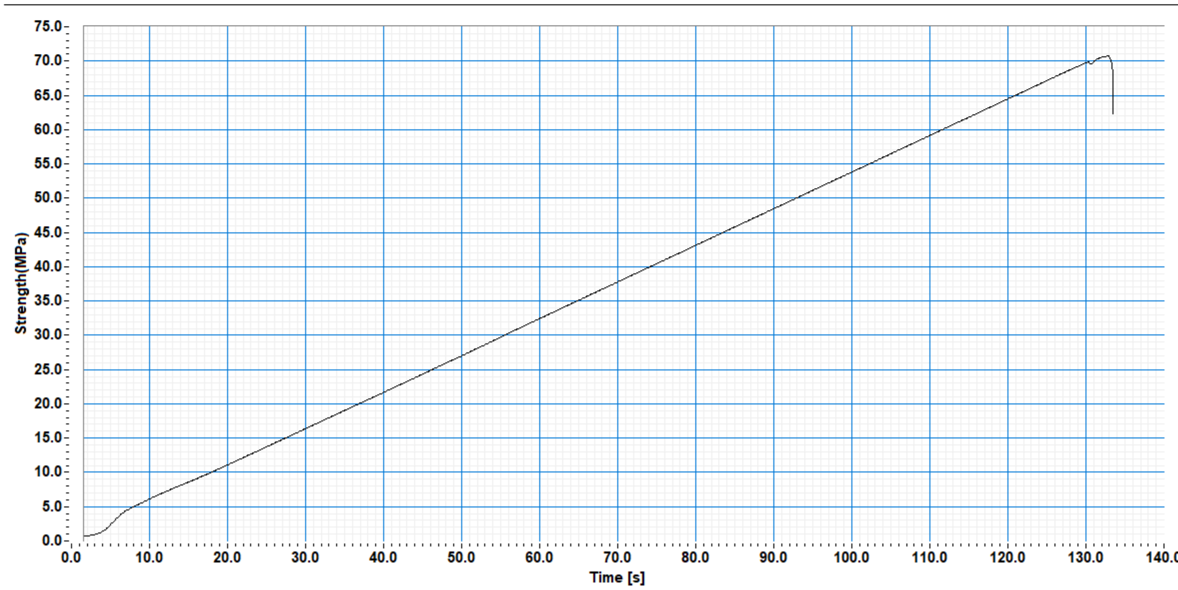
Test date : 02/28/20 - 21:33

Max Load [kN] : 176.86

Strength [MPa] : 70.74

Failure type

Notes :



Test Report A.8 Compressive Strength Report – Mix 1-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 1-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 1-3		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 14 Days

Specimen ID : 2

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0 Density [Kg/m3] : 0.0 Mass [Kg] : 0.000

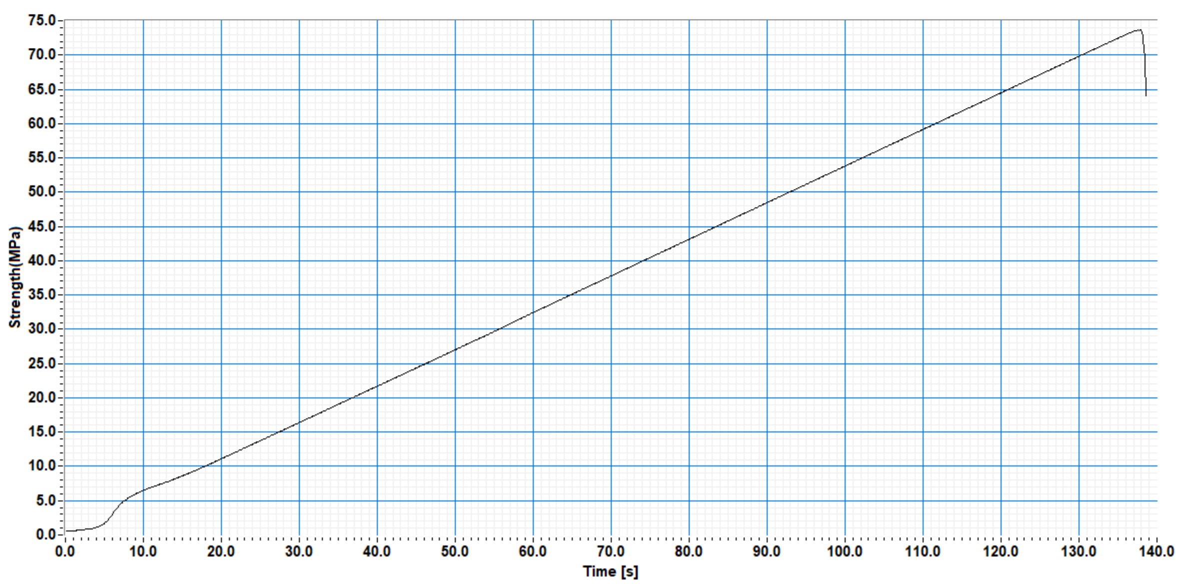
: : Specimen age [gg] : 28 days

Load Rate(N/s) : 1335.229 Test date : 02/28/20 - 21:37

Max Load [kN] : 184.10 **Strength [MPa] : 73.64**

Failure type

Notes :



Test Report A.9 Compressive Strength Report – Mix 1-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 1-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 1-3		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 14 Days

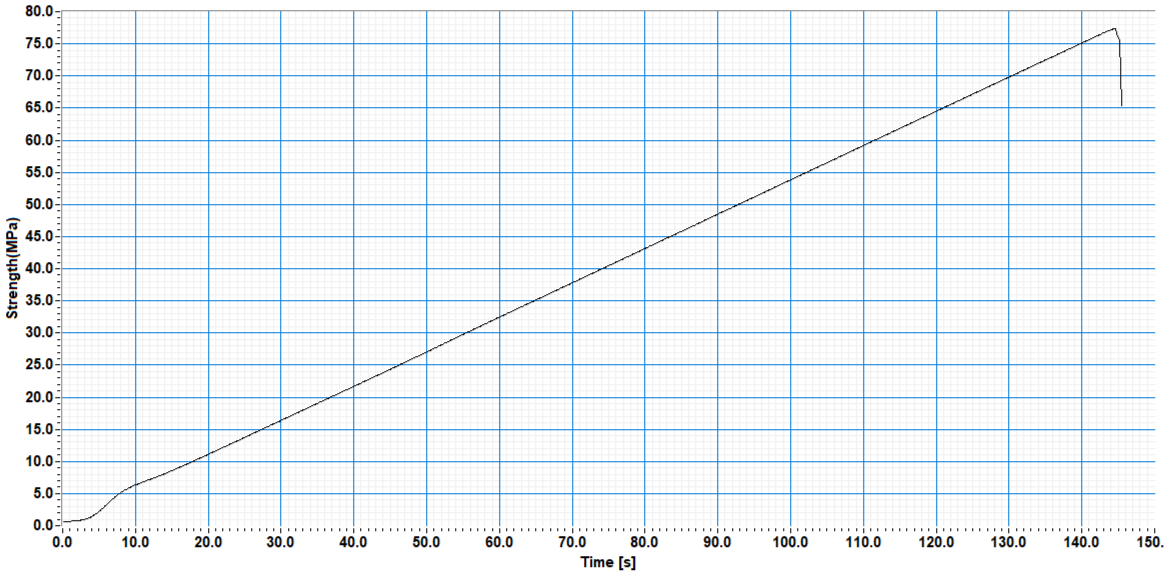
Specimen ID : 3

Dimensions	:	a(mm) 50.00		b(mm) 50.00		c(mm) 50.00	
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000		
	:		:	Specimen age [gg]	: 28 days		
Load Rate(N/s)	: 1334.897	Test date	: 02/28/20 - 21:37				

Max Load [kN] : 193.41 **Strength [MPa] : 77.36**

Failure type

Notes :



Test Report A.10 Compressive Strength Report – Mix 1-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 1-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 1-3		
Specimen type	: Cube	Admixture 2	: Sika control NS
Admixture 1	: Sika Viscocrete 2100		

Sample conditions:

Curing Time : 28 Days

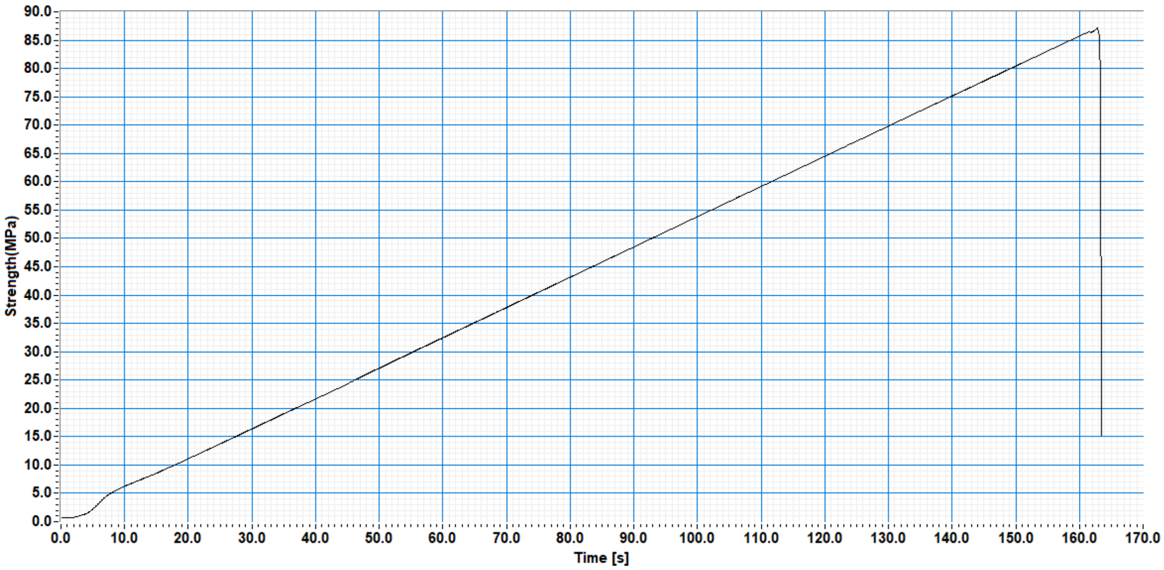
Specimen ID : 1

Dimensions	: a(mm)	50.00	b(mm)	50.00	c(mm)	50.00	
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0		Mass [Kg]	: 0.000	
	:		:		Specimen age [gg]	: 28 days	
Load Rate(N/s)	: 1334.210		Test date	: 03/13/20 - 18:23			

Max Load [kN] : 217.79 **Strength [MPa] : 87.12**

Failure type

Notes :



Test Report A.11 Compressive Strength Report – Mix 1-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 1-3

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 1-3

Specimen type : Cube

Admixture 2 : Sika control NS

Admixture 1 : Sika Viscocrete 2100

Sample conditions:

Curing Time : 28 Days

Specimen ID : 2

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0

Density [Kg/m3] : 0.0

Mass [Kg] : 0.000

:

:

Specimen age [gg] : 28 days

Load Rate(N/s) : 1334.911

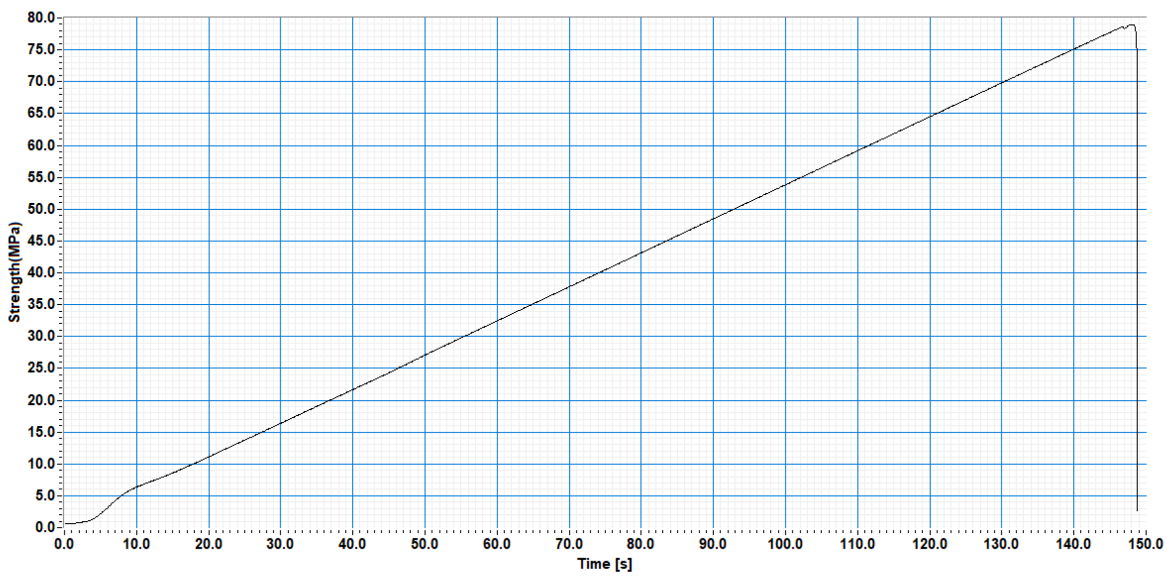
Test date : 03/13/20 - 18:23

Max Load [kN] : 197.34

Strength [MPa] : 78.94

Failure type

Notes :



Test Report A.12 Compressive Strength Report – Mix 1-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 1-3

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 1-3

Specimen type : Cube

Admixture 2 : Sika control NS

Admixture 1 : Sika Viscocrete 2100

Sample conditions:

Curing Time : 28 Days

:

Specimen ID : 3

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0 Density [Kg/m3] : 0.0 Mass [Kg] : 0.000

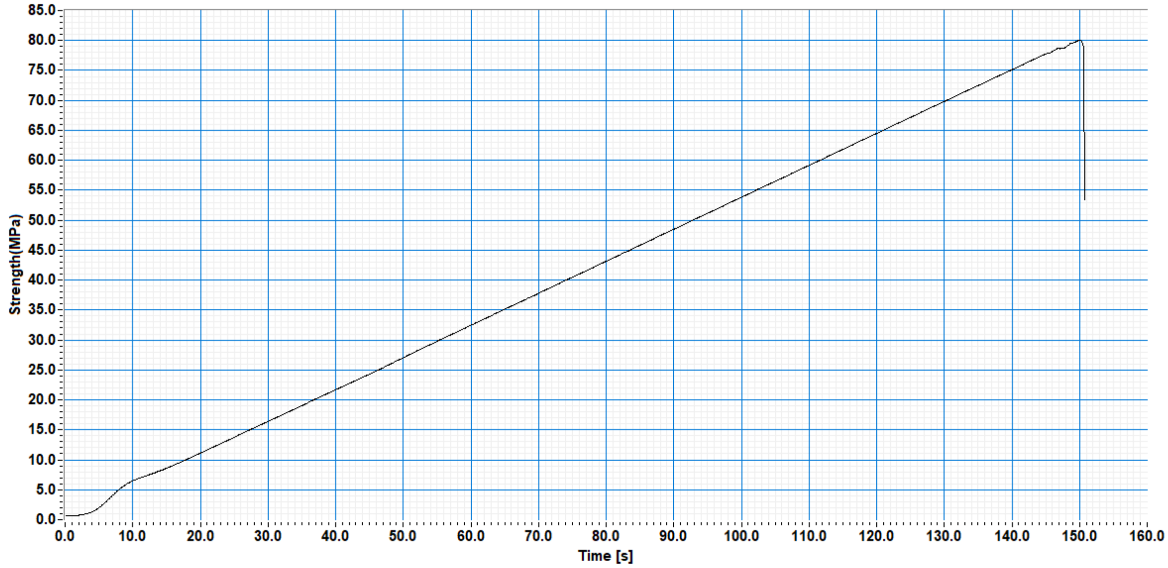
: : Specimen age [gg] : 28 days

Load Rate(N/s) : 1334.648 Test date : 03/13/20 - 18:23

Max Load [kN] : 200.17 Strength [MPa] : 80.07

Failure type

Notes :



Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 1-4

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 1-4

Specimen type : Cube

Admixture 2 : Sika control NS

Admixture 1 : Sika Viscocrete 2100

Sample conditions:

Curing Time : 28 Days

:

Specimen ID : 1

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0

Density [Kg/m3] : 0.0

Mass [Kg] : 0.000

:

:

Specimen age [gg] : 28 days

Load Rate(N/s) : 1336.004

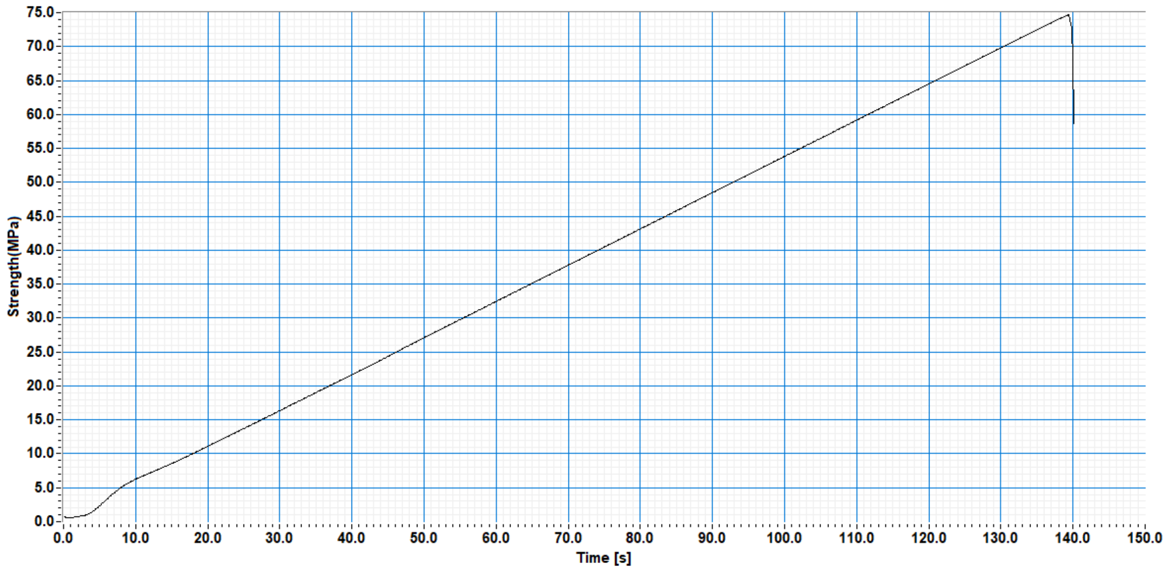
Test date : 03/13/20 - 18:23

Max Load [kN] : 186.64

Strength [MPa] : 74.66

Failure type

Notes :



Test Report A.14 Compressive Strength Report – Mix 1-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 1-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 1-4		
Specimen type	: Cube	Admixture 2	: Sika control NS
Admixture 1	: Sika Viscocrete 2100		

Sample conditions:

Curing Time : 28 Days

:

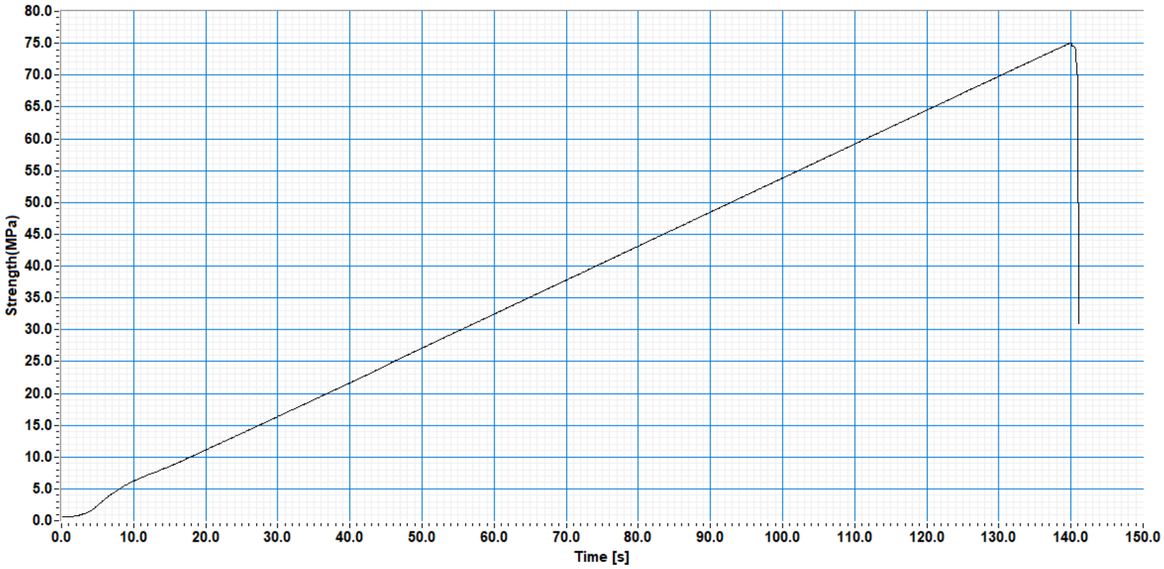
Specimen ID : 2

Dimensions	: a(mm)	50.00	b(mm)	50.00	c(mm)	50.00	
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000		
	:		:	Specimen age [gg]	: 28 days		
Load Rate(N/s)	: 1335.890	Test date	: 03/13/20 - 18:23				

Max Load [kN] : 187.59 **Strength [MPa] : 75.04**

Failure type

Notes :



Test Report A.15 Compressive Strength Report – Mix 1-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 1-4

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 1-4

Specimen type : Cube   Admixture 2 : Sika control NS

Admixture 1 : Sika Viscocrete 2100

Sample conditions:

Curing Time : 28 Days

Specimen ID : 3

Dimensions : a(mm) 50.00   b(mm) 50.00   c(mm) 50.00

Area [mm2] : 2500.0   Density [Kg/m3] : 0.0   Mass [Kg] : 0.000

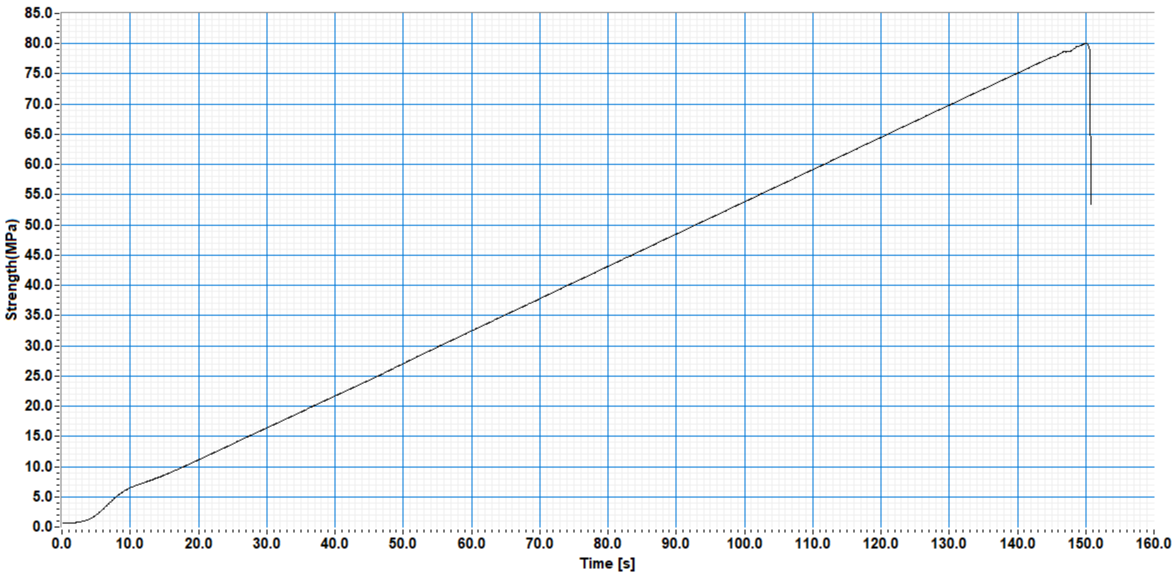
:   :   Specimen age [gg] : 28 days

Load Rate(N/s) : 1334.648   Test date : 03/13/20 - 18:23

Max Load [kN] : 200.17   Strength [MPa] : 80.07

Failure type

Notes :



Test Report A.16 Compressive Strength Report – Mix 2-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 2-3

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 2-3

Specimen type : Cube   Admixture 2 : MasterLife CRA 007

Admixture 1 : BASF MasterGlenium 7620

Sample conditions:

Curing Time : 14 Days

Specimen ID : 1

Dimensions : a(mm) 50.00   b(mm) 50.00   c(mm) 50.00

Area [mm2] : 2500.0   Density [Kg/m3] : 0.0   Mass [Kg] : 0.000

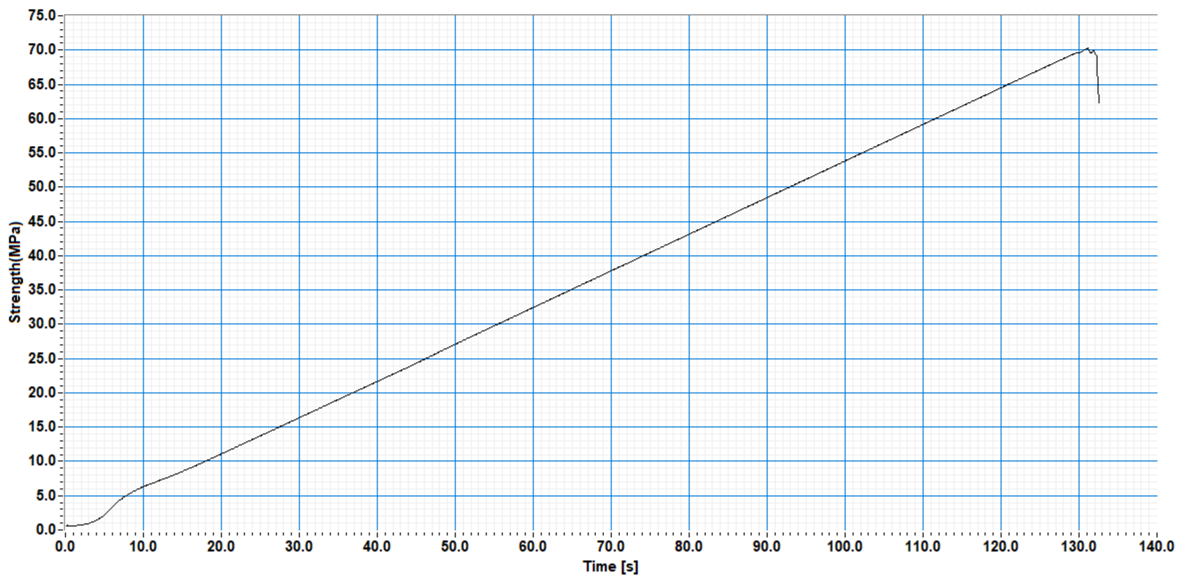
:   :   Specimen age [gg] : 28 days

Load Rate(N/s) : 1335.734   Test date : 03/08/20 - 13:09

Max Load [kN] : 175.65   Strength [MPa] : 70.26

Failure type

Notes :



Test Report A.17 Compressive Strength Report – Mix 2-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	:		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

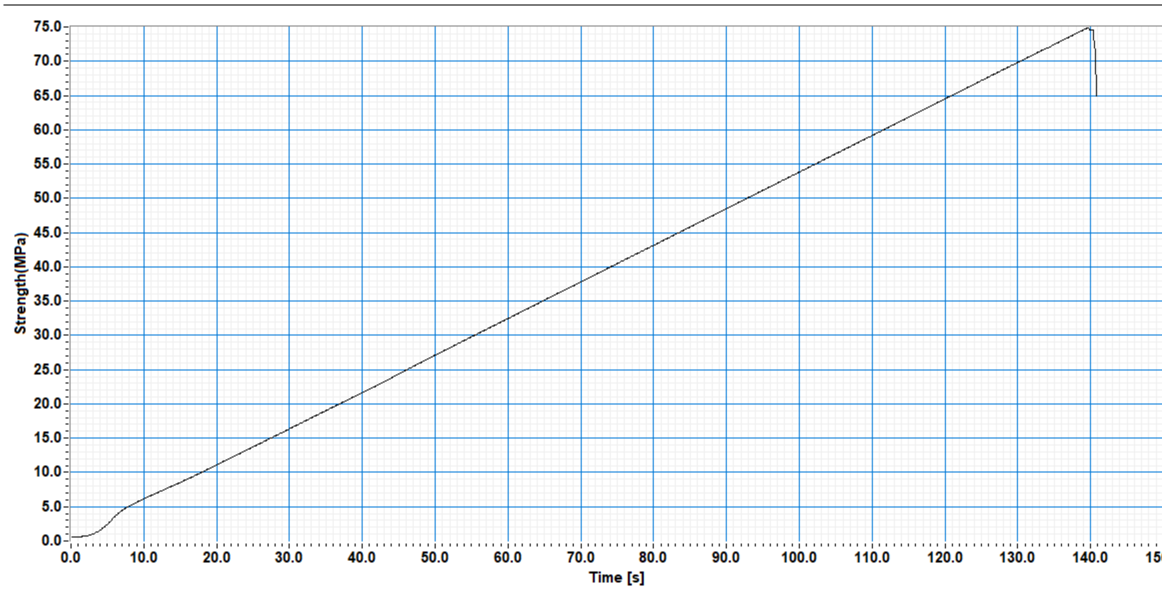
Curing Time	: 14 Days
Specimen ID	: 2

Dimensions	: a(mm) 50.00		b(mm) 50.00		c(mm) 50.00	
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000	
	:		:	Specimen age [gg]	: 28 days	
Load Rate(N/s)	: 1335.860	Test date	: 03/08/20 - 13:09			

Max Load [kN] **: 187.23** **Strength [MPa]** **: 74.89**

Failure type

Notes :



Test Report A.18 Compressive Strength Report – Mix 2-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-3		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 14 Days

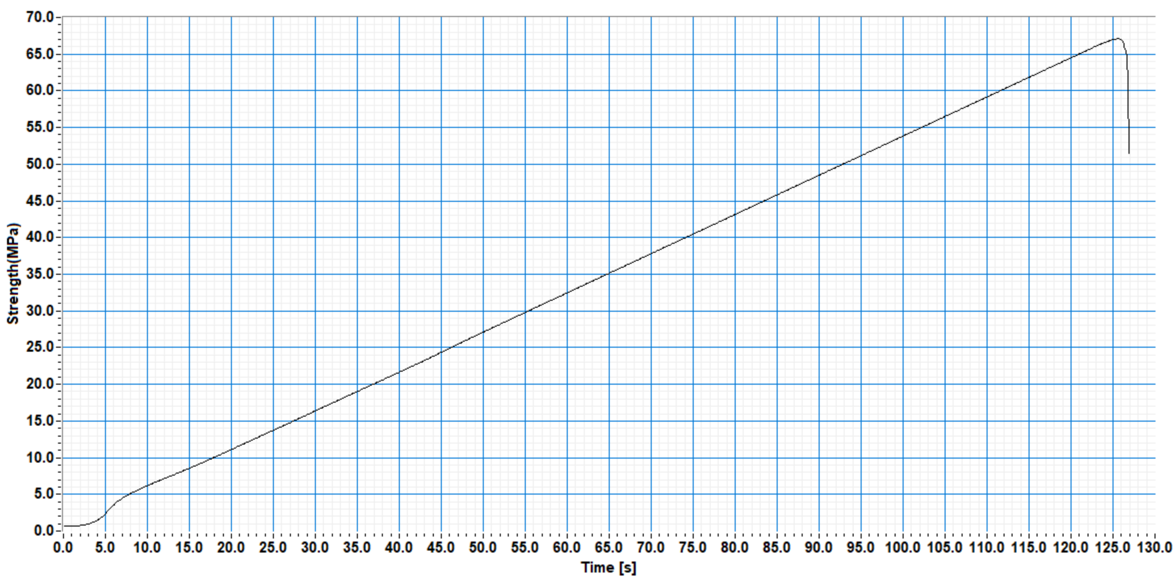
Specimen ID : 3

Dimensions :	a(mm) 50.00	b(mm) 50.00	c(mm) 50.00		
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1336.035	Test date	: 03/08/20 - 13:09		

Max Load [kN] : 167.99 **Strength [MPa] : 67.20**

Failure type

Notes :



Test Report A.19 Compressive Strength Report – Mix 2-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-3		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 28 Days

Specimen ID : 1

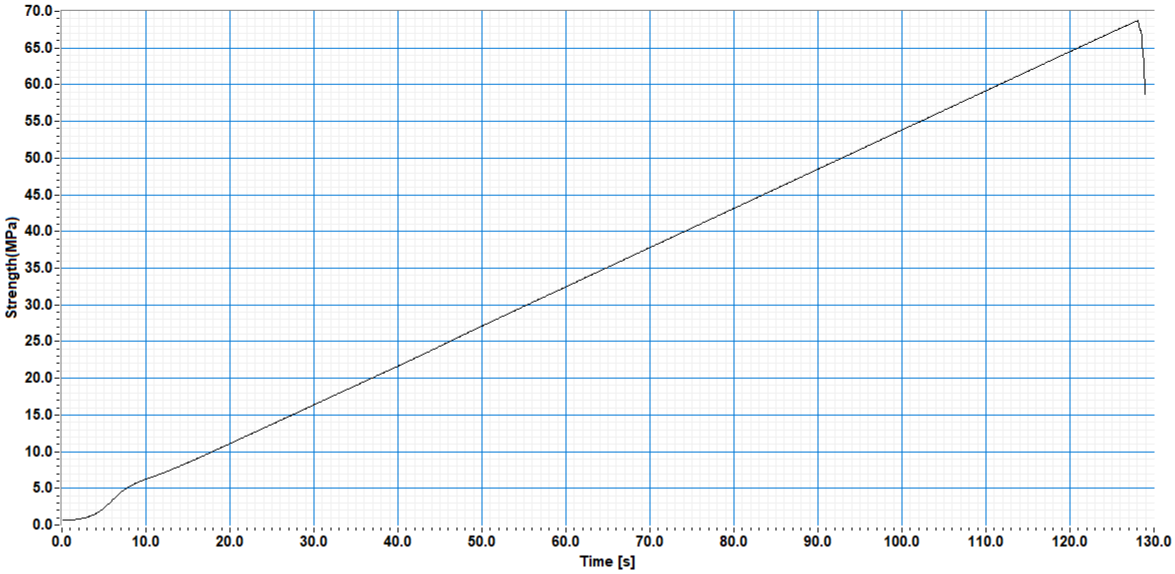
Dimensions	: a(mm)	50.00	b(mm)	50.00	c(mm)	50.00

Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1336.227	Test date			: 03/22/20 - 17:41

Max Load [kN] : 171.78 **Strength [MPa] : 68.71**

Failure type

Notes :



Test Report A.20 Compressive Strength Report – Mix 2-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 2-3

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 2-3

Specimen type : Cube

Admixture 2 : MasterLife CRA 007

Admixture 1 : BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

Specimen ID : 2

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0

Density [Kg/m3] : 0.0

Mass [Kg] : 0.000

:

:

Specimen age [gg] : 28 days

Load Rate(N/s) : 1336.117

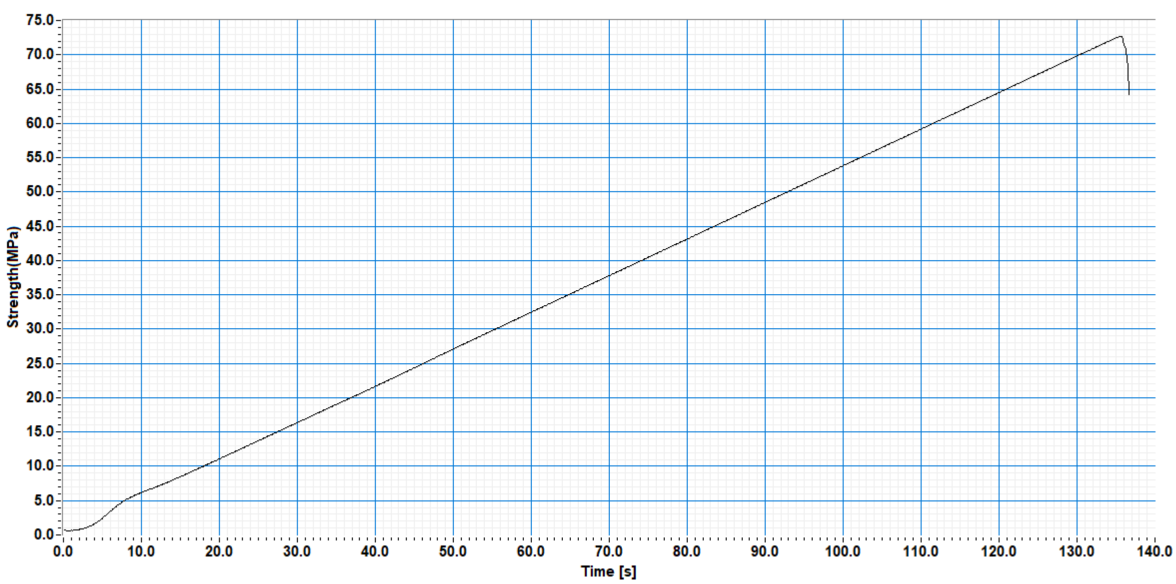
Test date : 03/22/20 - 17:41

Max Load [kN] : 181.81

Strength [MPa] : 72.72

Failure type

Notes :



Test Report A.21 Compressive Strength Report – Mix 2-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-3		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 28 Days

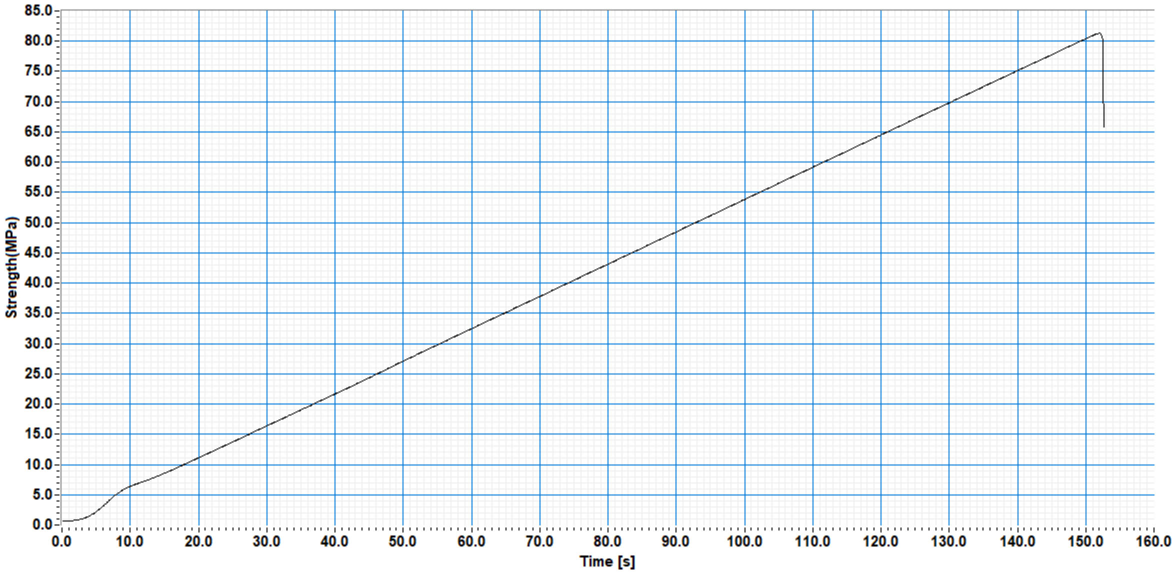
Specimen ID : 3

Dimensions	: a(mm) 50.00	b(mm)	50.00	c(mm)	50.00		
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000		
	:		:	Specimen age [gg]	: 28 days		
Load Rate(N/s)	: 1334.457	Test date	: 03/22/20 - 17:41				

Max Load [kN] **: 203.30** **Strength [MPa]** **: 81.32**

Failure type

Notes :



Test Report A.22 Compressive Strength Report – Mix 2-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-4		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 14 Days

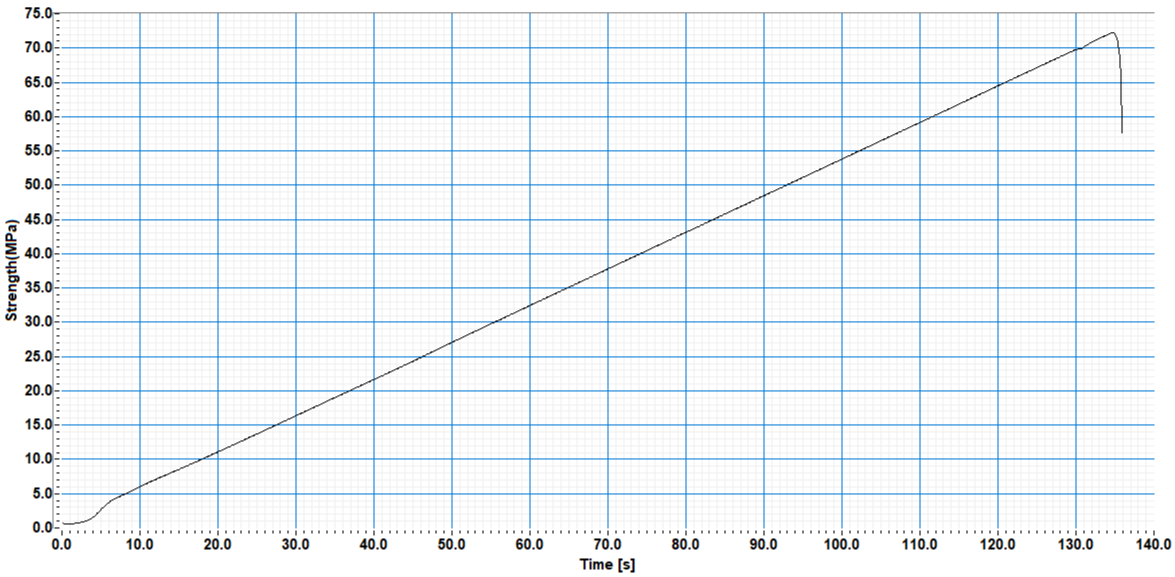
Specimen ID : 1

Dimensions	: a(mm) 50.00	b(mm) 50.00		c(mm) 50.00	
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1336.118	Test date		: 03/08/20 - 12:56	

Max Load [kN] **: 180.64** **Strength [MPa]** **: 72.26**

Failure type

Notes :



Test Report A.23 Compressive Strength Report – Mix 2-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-4		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 14 Days

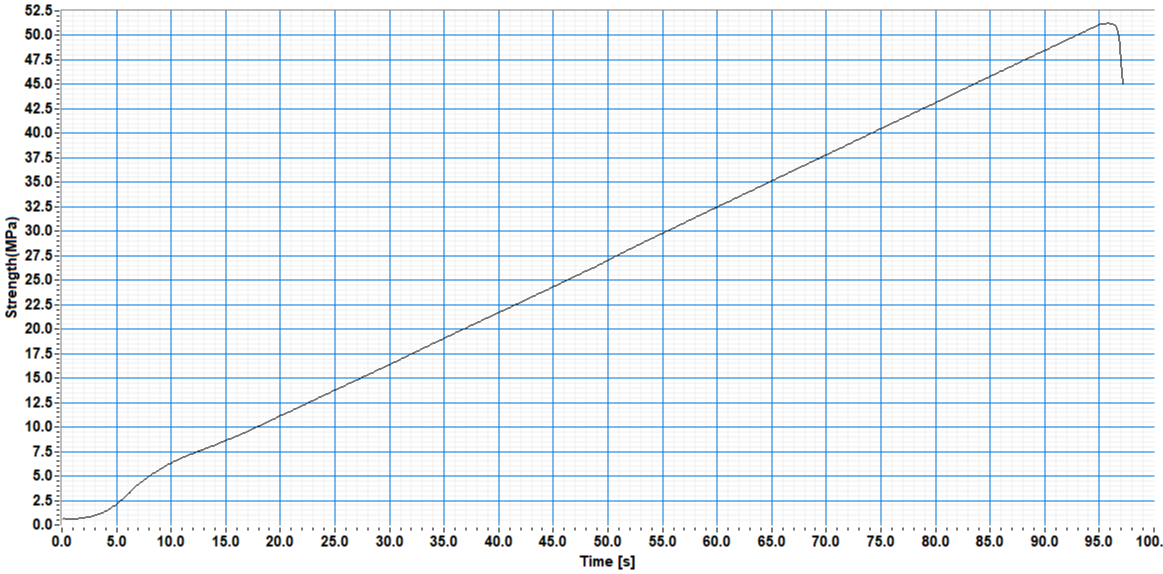
Specimen ID : 2

Dimensions	:	a(mm)	50.00	b(mm)	50.00	c(mm)	50.00		
Area [mm2]	:	2500.0		Density [Kg/m3]	:	0.0	Mass [Kg]	:	0.000
	:				:		Specimen age [gg]	:	28 days
Load Rate(N/s)	:	1332.832		Test date	:	03/08/20 - 12:56			

Max Load [kN] **: 128.18** **Strength [MPa]** **: 51.27**

Failure type

Notes :



Test Report A.24 Compressive Strength Report – Mix 2-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-4		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time	: 14 Days
Specimen ID	: 3

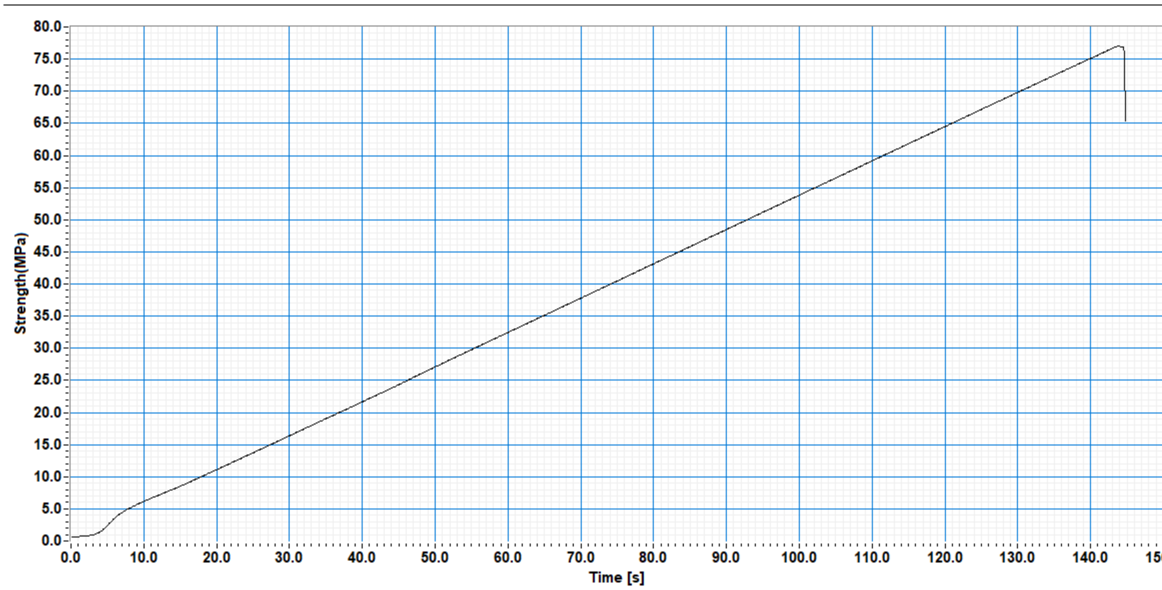
Dimensions	: a(mm)	50.00	b(mm)	50.00	c(mm)	50.00

Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1335.543	Test date		: 03/08/20 - 12:56	

Max Load [kN] **: 192.60** **Strength [MPa]** **: 77.04**

Failure type

Notes :



Test Report A.25 Compressive Strength Report – Mix 2-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-4		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 28 Days

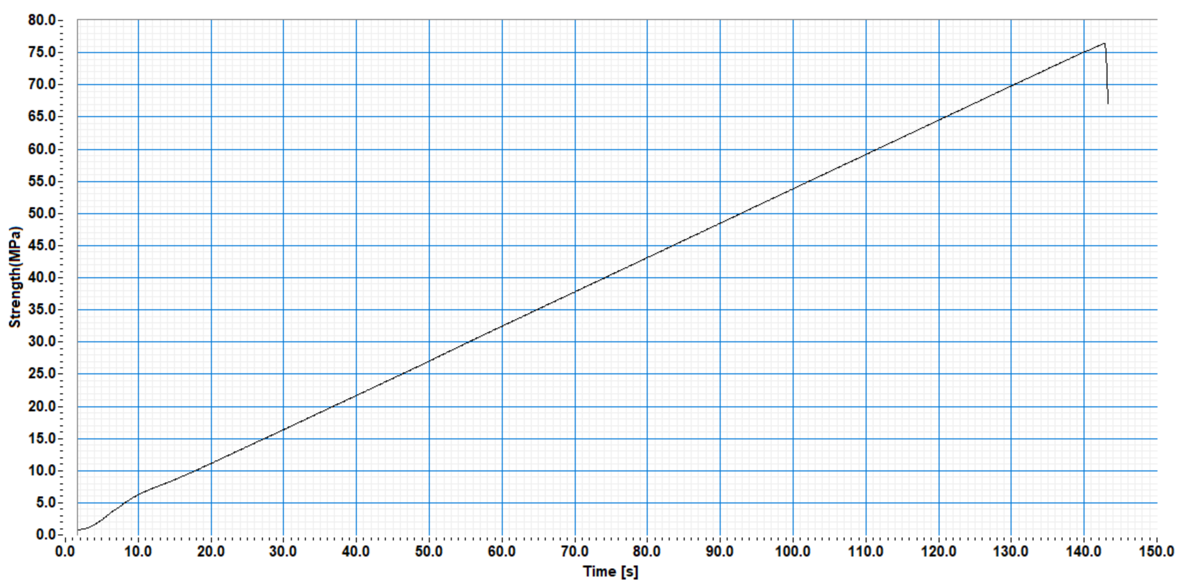
Specimen ID : 1

Dimensions	: a(mm) 50.00	b(mm) 50.00	c(mm) 50.00		
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1335.540	Test date	: 03/22/20 - 17:41		

Max Load [kN] : 191.23 **Strength [MPa] : 76.49**

Failure type

Notes :



Test Report A.26 Compressive Strength Report – Mix 2-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-4		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time	: 28 Days
	:
	:
Specimen ID	: 2

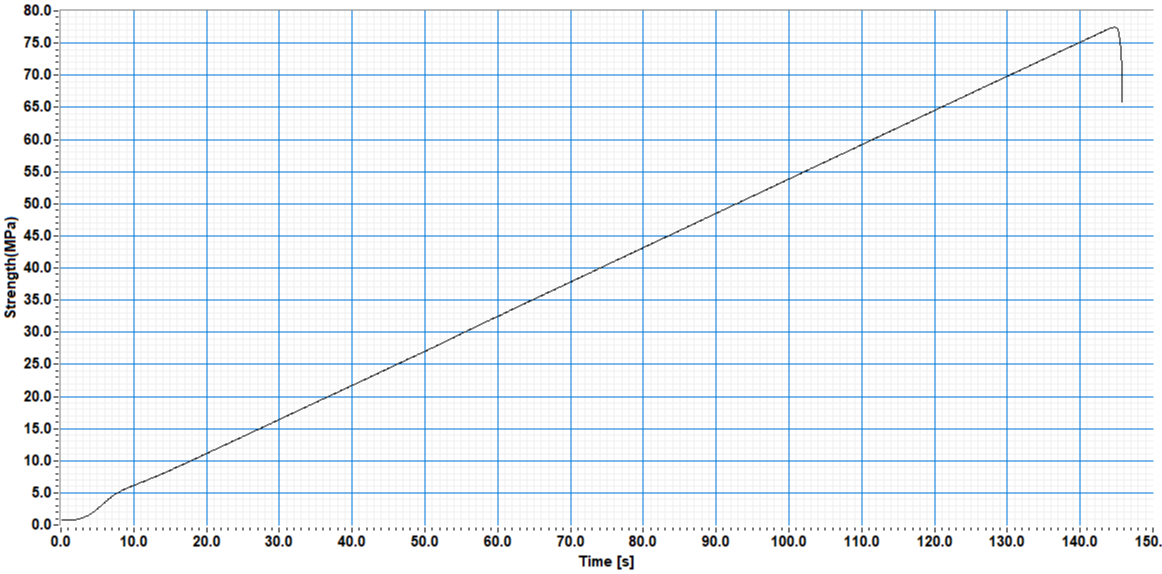
Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1334.996	Test date			: 03/22/20 - 17:41

Max Load [kN] : 193.80 **Strength [MPa] : 77.52**

Failure type

Notes :



Test Report A.27 Compressive Strength Report – Mix 2-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 2-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-4		
Specimen type	: Cube	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 28 Days

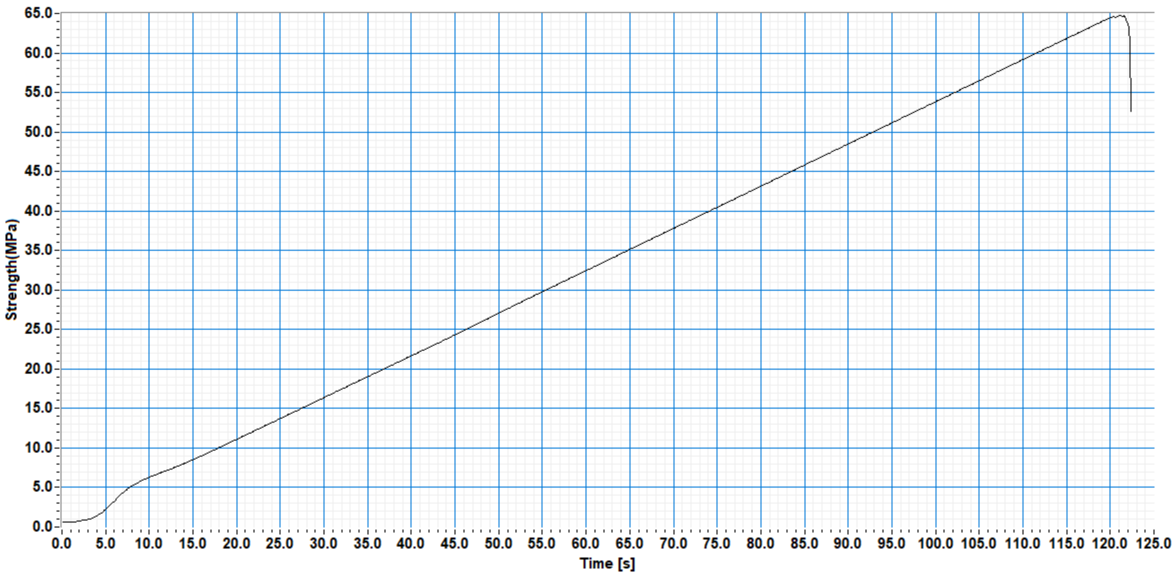
Specimen ID : 3

Dimensions	:	a(mm)	50.00	b(mm)	50.00	c(mm)	50.00
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000		
	:		:	Specimen age [gg]	: 28 days		
Load Rate(N/s)	: 1335.778	Test date	: 03/22/20 - 17:41				

Max Load [kN] : 162.00 **Strength [MPa] : 64.80**

Failure type

Notes :



Test Report A.28 Compressive Strength Report – Mix 3-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-3		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620	Specimen preparation date	: 02/07/20

Sample conditions:

Curing Time : 14 Days

Specimen ID : 1

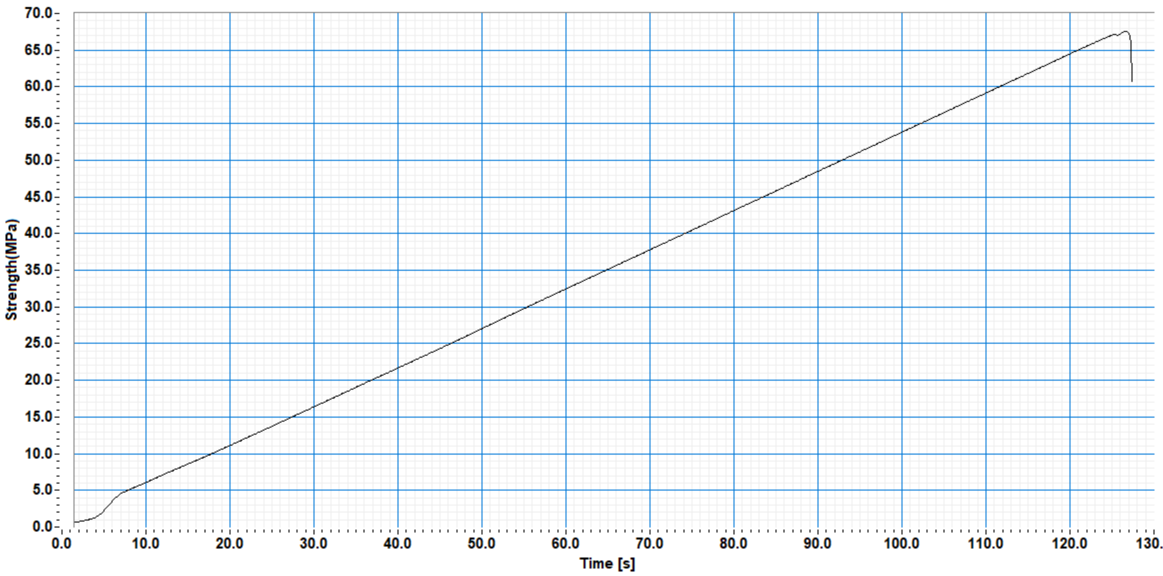
Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1335.870	Test date	: 02/21/20 - 16:41		

Max Load [kN] : 168.90 **Strength [MPa] : 67.56**

Failure type

Notes :



Test Report A.29 Compressive Strength Report – Mix 3-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-3		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620	Specimen preparation date	: 02/07/20

Sample conditions:

Curing Time : 14 Days

Specimen ID : 2

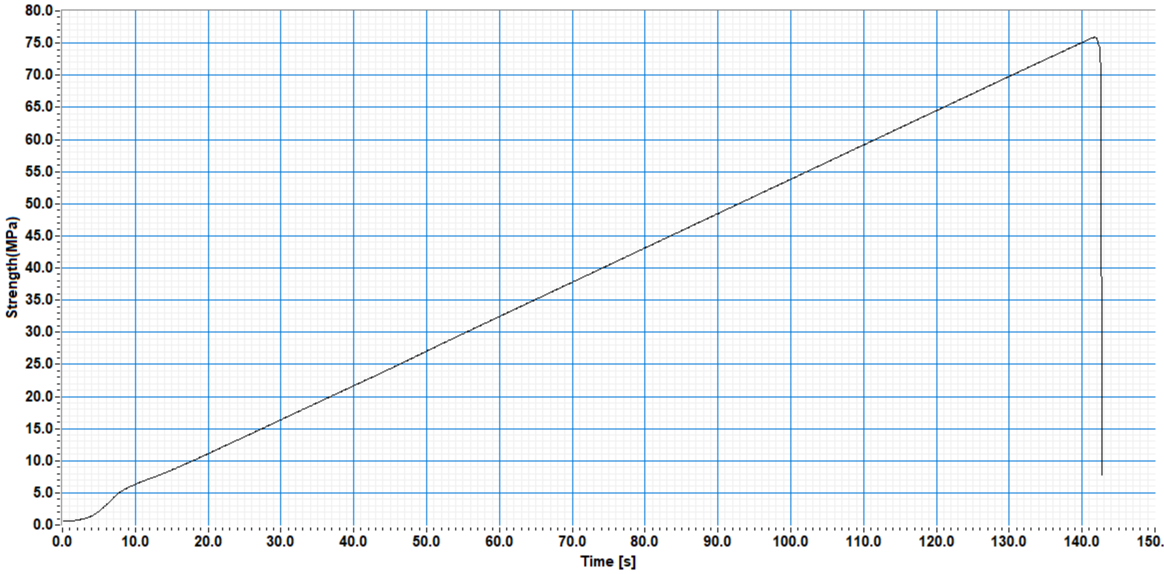
Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1335.340		Test date	: 02/21/20 - 16:48	

Max Load [kN] : 189.82 **Strength [MPa] : 75.93**

Failure type

Notes :



Test Report A.30 Compressive Strength Report – Mix 3-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-3		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620	Specimen preparation date	: 02/07/20

Sample conditions:

Curing Time : 14 Days

Specimen ID : 3

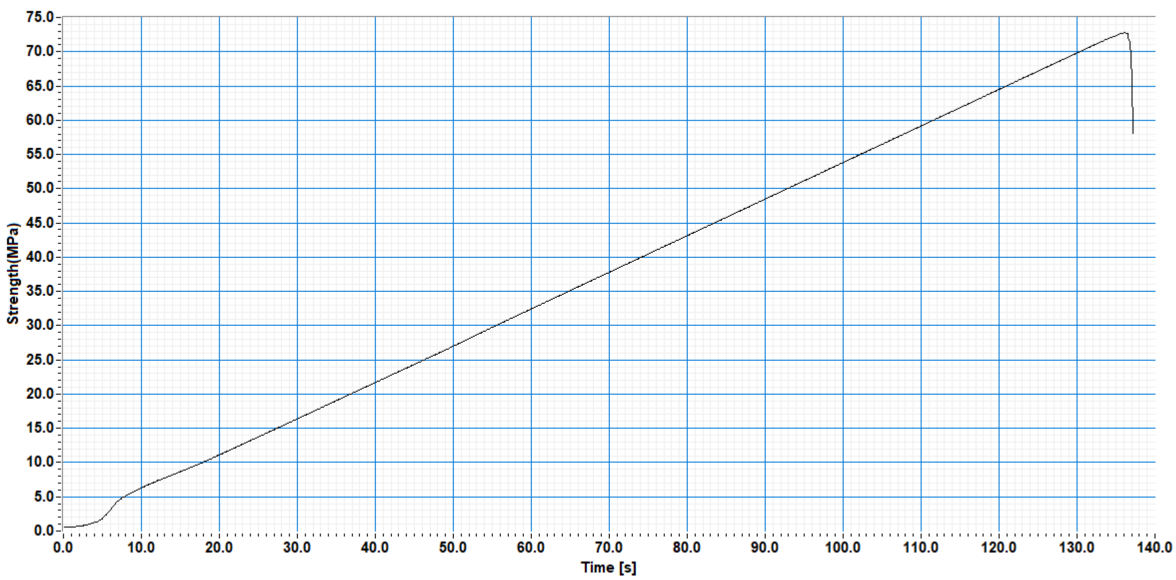
Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0	Density [Kg/m3] : 0.0	Mass [Kg]	: 0.000
:	:	Specimen age [gg]	: 28 days
Load Rate(N/s) : 1334.936	Test date	: 02/21/20 - 16:52	

Max Load [kN] : 181.92 **Strength [MPa] : 72.77**

Failure type

Notes :



Test Report A.31 Compressive Strength Report – Mix 3-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-3		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 28 Days

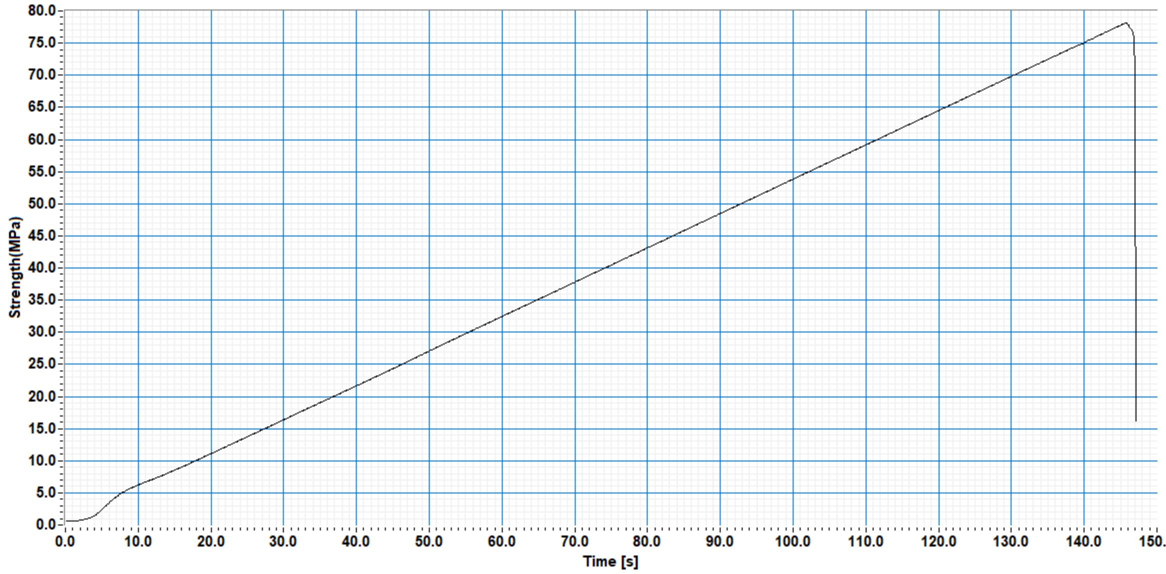
Specimen ID : 1

Dimensions	:	a(mm)	50.00	b(mm)	50.00	c(mm)	50.00
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000		
	:		:	Specimen age [gg]	: 28 days		
Load Rate(N/s)	: 1335.013	Test date	: 03/22/20 - 17:41				

Max Load [kN] : 195.50 **Strength [MPa] : 78.20**

Failure type

Notes :



Test Report A.32 Compressive Strength Report – Mix 3-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 3-3

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 3-3

Specimen type : Cube

Admixture 2 : MasterLife SRA 035

Admixture 1 : BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

Specimen ID : 2

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0 Density [Kg/m3] : 0.0 Mass [Kg] : 0.000

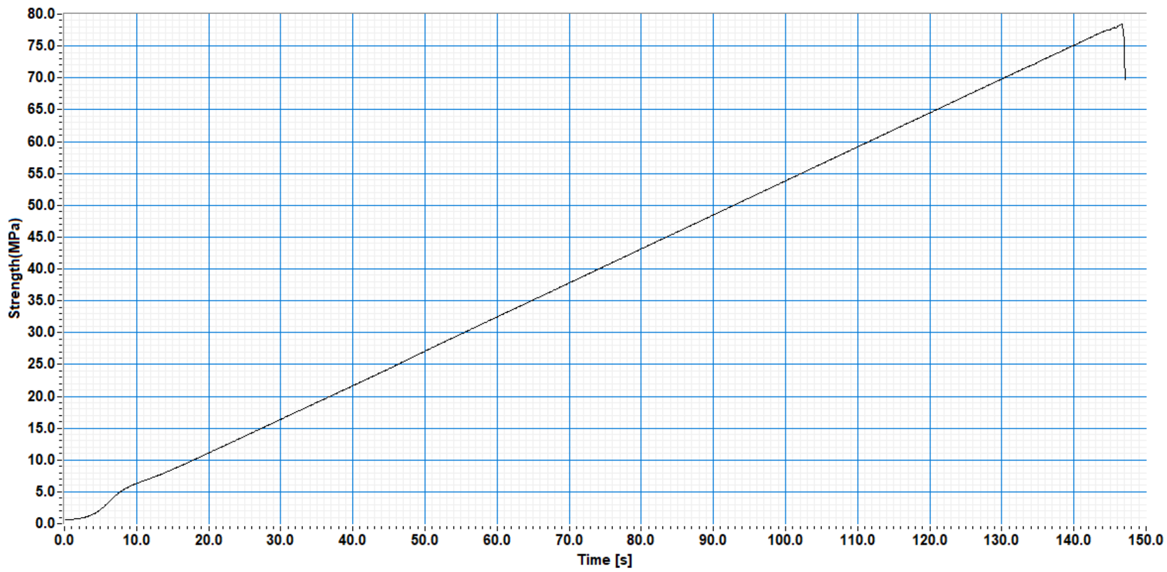
: : Specimen age [gg] : 28 days

Load Rate(N/s) : 1335.287 Test date : 03/22/20 - 17:41

Max Load [kN] : 196.01 **Strength [MPa] : 78.40**

Failure type

Notes :



Test Report A.33 Compressive Strength Report – Mix 3-3

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-3		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 28 Days

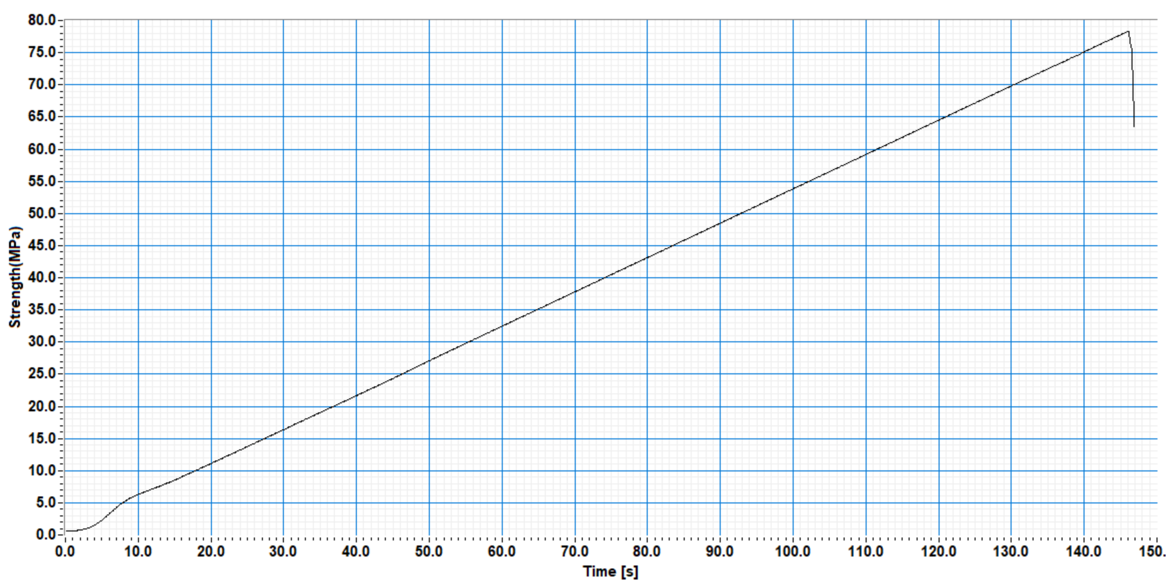
Specimen ID : 3

Dimensions	:	a(mm) 50.00	b(mm) 50.00		c(mm) 50.00		
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0		Mass [Kg]	:	0.000
	:		:		Specimen age [gg]	:	28 days
Load Rate(N/s)	: 1334.680		Test date		: 03/22/20 - 17:41		

Max Load [kN] : 195.81 **Strength [MPa] : 78.32**

Failure type

Notes :



Test Report A.34 Compressive Strength Report – Mix 3-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-4		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620	Specimen preparation date	: 02/07/20

Sample conditions:

Curing Time : 14 Days

Specimen ID : 1

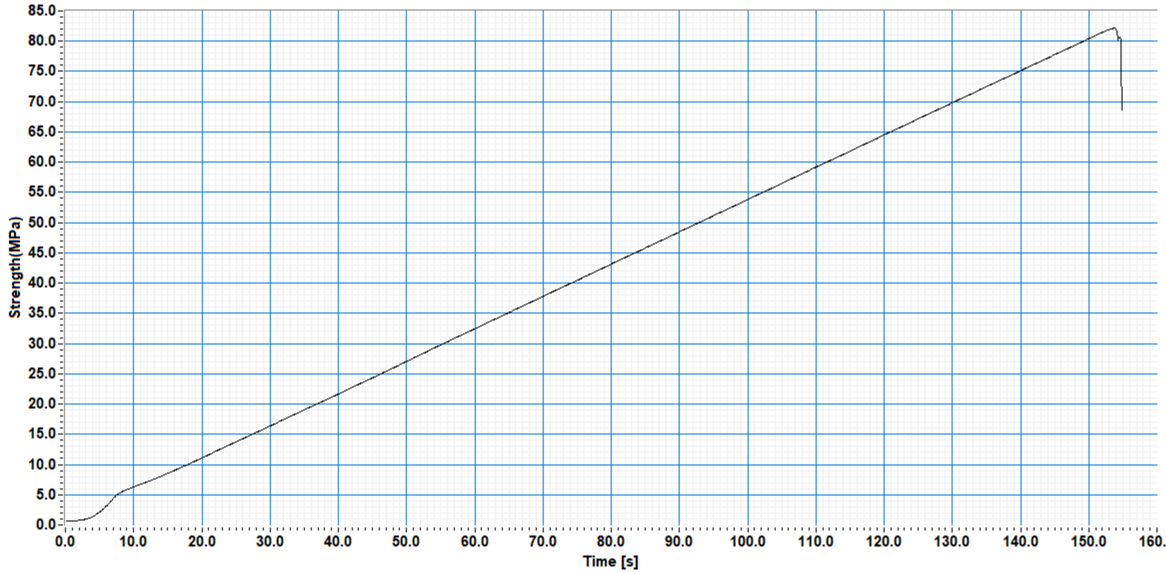
Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1334.576	Test date	: 02/21/20 - 16:56		

Max Load [kN] : 205.64 **Strength [MPa] : 82.26**

Failure type

Notes :



Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-4		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620	Specimen preparation date	: 02/07/20

Sample conditions:

Curing Time : 14 Days

Specimen ID : 2

Dimensions : a(mm) 50.00 b(mm) 50.00 c(mm) 50.00

Area [mm2] : 2500.0 Density [Kg/m3] : 0.0 Mass [Kg] : 0.000

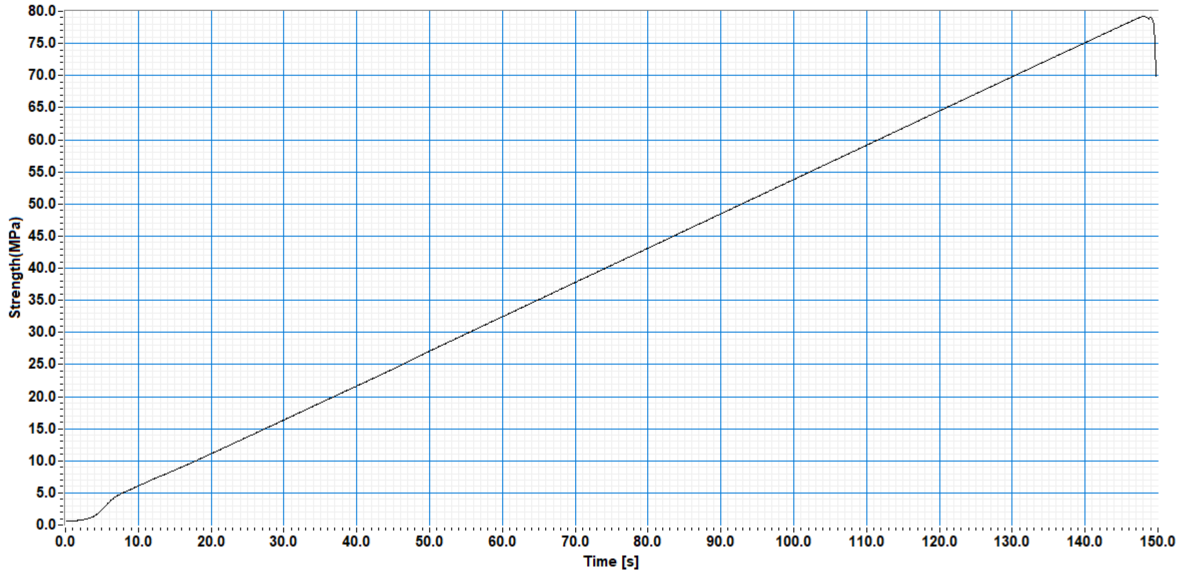
: : Specimen age [gg] : 28 days

Load Rate(N/s) : 1335.029 Test date : 02/21/20 - 17:01

Max Load [kN] : 198.14 **Strength [MPa] : 79.25**

Failure type

Notes :



Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-4		
Specimen type	: Cube	Admixture 2	:
Admixture 1	: BASF MasterGlenium 7620	Specimen preparation date	: 02/07/20

Sample conditions:

Curing Time : 14 Days

Specimen ID : 3

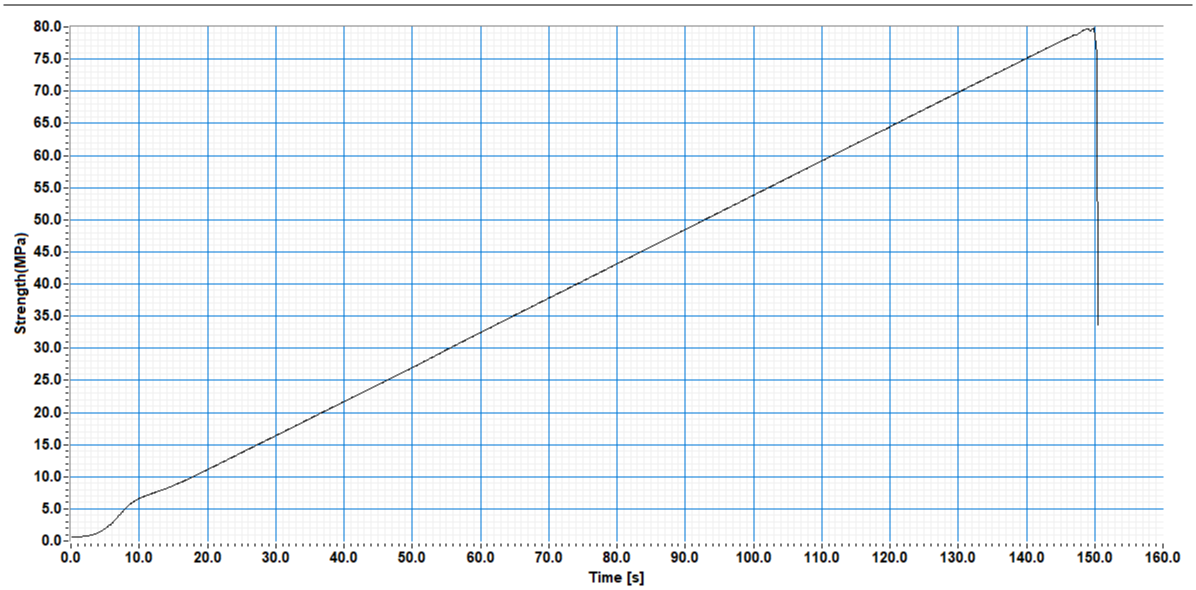
Dimensions	:	a(mm)	50.00	b(mm)	50.00	c(mm)	50.00

Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0	Mass [Kg]	: 0.000
	:		:	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 1334.582	Test date	: 02/21/20 - 17:05		

Max Load [kN] **: 199.46** **Strength [MPa]** **: 79.78**

Failure type

Notes :



Test Report A.37 Compressive Strength Report – Mix 3-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 3-4

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 3-4

Specimen type : Cube   Admixture 2 :

Admixture 1 : BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

Specimen ID : 1

Dimensions : a(mm) 50.00   b(mm) 50.00   c(mm) 50.00

Area [mm2] : 2500.0   Density [Kg/m3] : 0.0   Mass [Kg] : 0.000

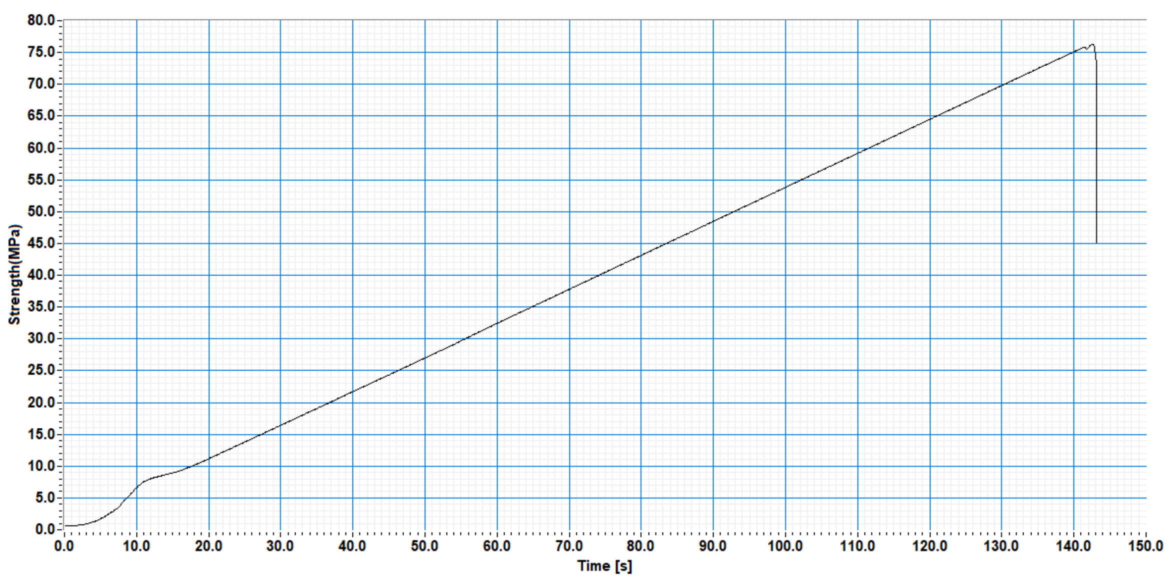
: :   Specimen age [gg] : 28 days

Load Rate(N/s) : 1334.337   Test date : 03/22/20 - 17:41

Max Load [kN] : 190.80   Strength [MPa] : 76.32

Failure type

Notes :



Test Report A.38 Compressive Strength Report – Mix 3-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No. : Mix 3-4

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 3-4

Specimen type : Cube   Admixture 2 : MasterLife SRA 035

Admixture 1 : BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

Specimen ID : 2

Dimensions : a(mm) 50.00   b(mm) 50.00   c(mm) 50.00

Area [mm2] : 2500.0   Density [Kg/m3] : 0.0   Mass [Kg] : 0.000

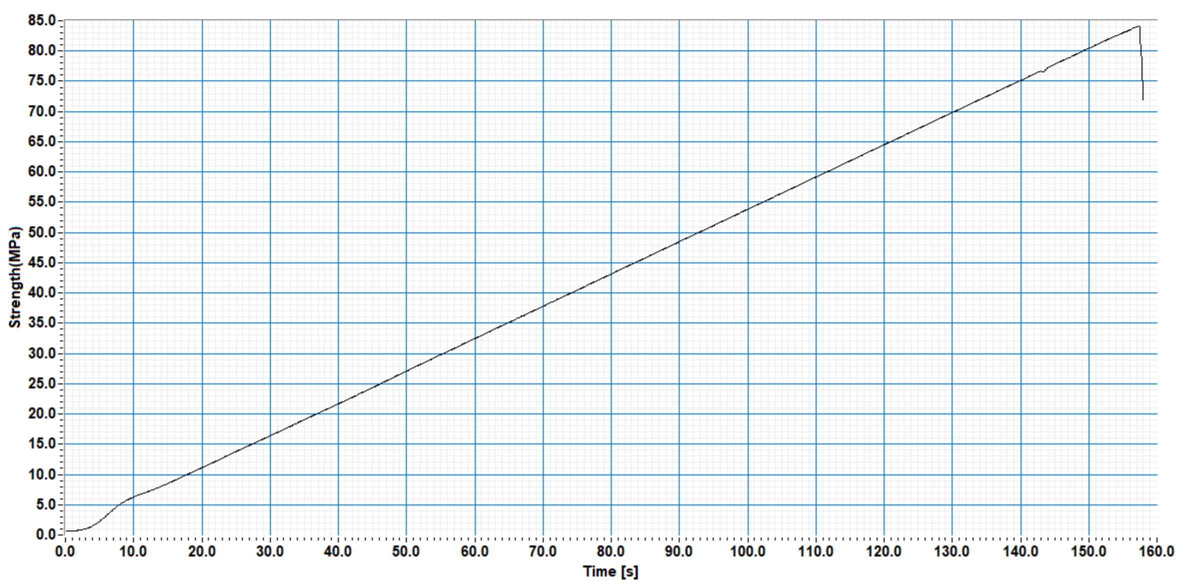
:   :   Specimen age [gg] : 28 days

Load Rate(N/s) : 1334.888   Test date : 03/22/20 - 17:41

Max Load [kN] : 210.27   Strength [MPa] : 84.11

Failure type

Notes :



Test Report A.39 Compressive Strength Report – Mix 3-4

Syracuse University

Compression on mortar cubes: ASTM C109

Mix No.	: Mix 3-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-4		
Specimen type	: Cube	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

Curing Time : 28 Days

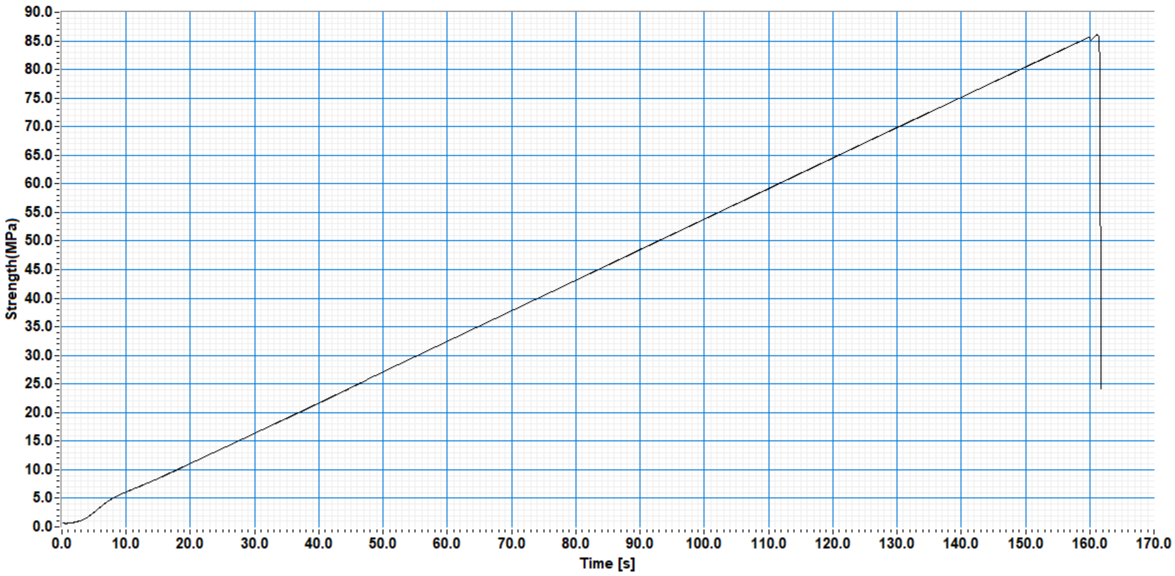
Specimen ID : 3

Dimensions	: a(mm)	50.00	b(mm)	50.00	c(mm)	50.00	
Area [mm2]	: 2500.0	Density [Kg/m3]	: 0.0		Mass [Kg]	: 0.000	
	:		:		Specimen age [gg]	: 28 days	
Load Rate(N/s)	: 1334.241		Test date	: 03/22/20 - 17:41			

Max Load [kN] : 215.17 **Strength [MPa] : 86.07**

Failure type

Notes :



Test Report A.40 Bending Strength Report – Reference Mix

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Reference Mix				
Testing machine	: CONTROLS - Automax				
Client	: Syracuse University				
Reference	: Reference Mix				
Specimen type	: Beam	Admixture 2	: -		
Admixture 1	: Fosroc Cebex 305				

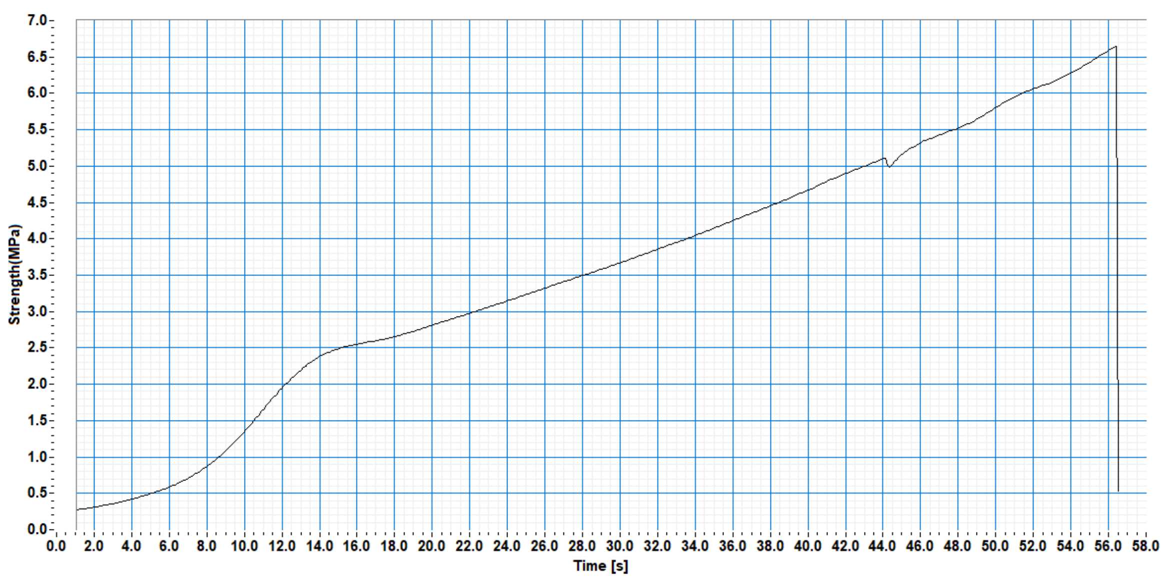
Sample conditions:

Curing Time	: 28 Days
Specimen ID	: 1

Dimensions	: b(mm) 40.00	h(mm) 40.00		l(mm) 160.00	
Area [mm2]	: 426.7		:	Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 45.242	Test date		: 03/12/20 - 12:40	

Max Load [kN] **: 2.84** **Strength [MPa]** **: 6.65**

Notes :



Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Reference Mix		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Reference Mix		
Specimen type	: Beam	Admixture 2	: -
Admixture 1	: Fosroc Cebex 305		

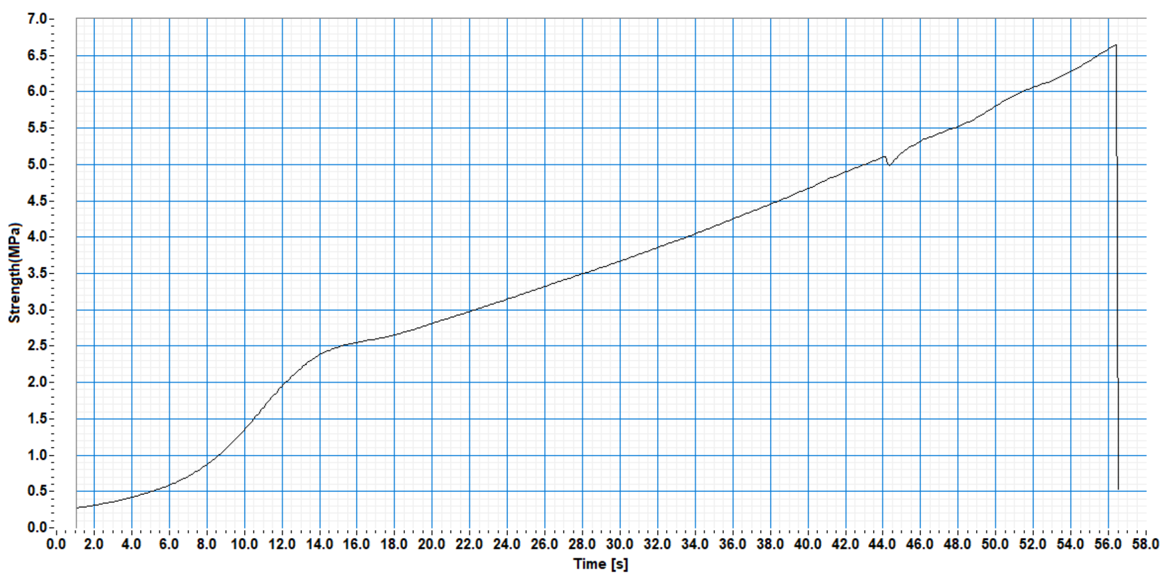
Sample conditions:

Curing Time	: 28 Days
Specimen ID	: 2

Dimensions	: b(mm) 40.00	h(mm)	40.00	l(mm)	160.00
Area [mm2]	: 426.7		:	Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 45.242	Test date			: 03/12/20 - 12:40

Max Load [kN] **: 2.84** **Strength [MPa]** **: 6.65**

Notes :



Test Report A.42 Bending Strength Report – Reference Mix

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Reference Mix		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Reference Mix		
Specimen type	: Beam	Admixture 2	: -
Admixture 1	: Fosroc Cebex 305		

Sample conditions:

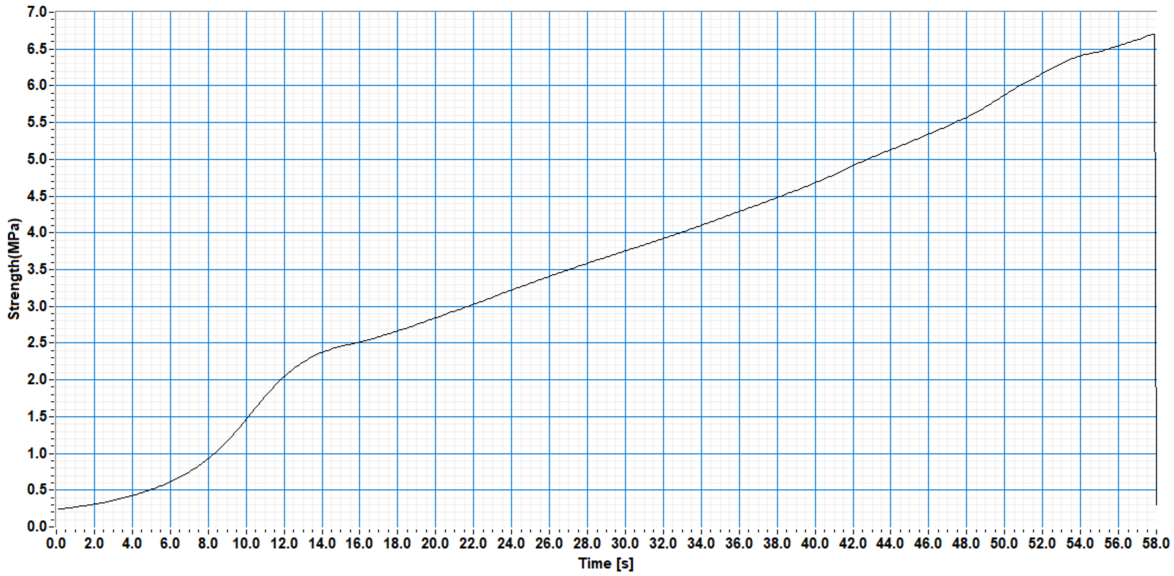
Curing Time : 28 Days

Specimen ID : 3

Dimensions	: b(mm) 40.00		h(mm) 40.00		l(mm) 160.00		
Area [mm2]	: 426.7		:		Mass [Kg]	: 0.000	
No of upper rollers	: 1	"L" distance [mm]	: 100.0		Specimen age [gg]	: 28 days	
Load Rate(N/s)	: 44.401	Test date	: 03/26/20 - 16:26				

Max Load [kN] **: 2.86** **Strength [MPa]** **: 6.70**

Notes :



Test Report A.43 Bending Strength Report – Mix 1-3

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 1-3
Testing machine	: CONTROLS - Automax
Client	: Syracuse University
Reference	: Mix 1-3
Specimen type	: Beam
Admixture 1	: Sika Viscocrete 2100
Admixture 2	: Sika control NS

Sample conditions:

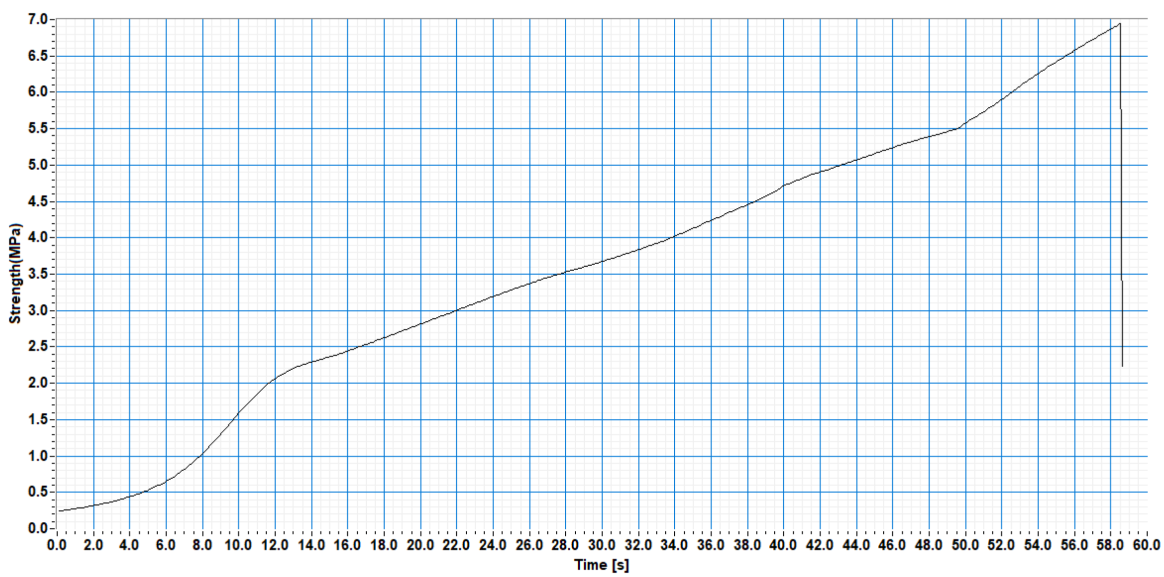
Curing Time : 28 Days

Specimen ID : 1

Dimensions	: b(mm) 40.00	h(mm) 40.00		l(mm) 160.00	
Area [mm2]	: 426.7		:	Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 43.776	Test date	: 03/26/20 - 16:26		

Max Load [kN] : 2.96 **Strength [MPa] : 6.94**

Notes :



Test Report A.44 Bending Strength Report – Mix 1-3

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 1-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 1-3		
Specimen type	: Beam	Admixture 2	: Sika control NS
Admixture 1	: Sika Viscocrete 2100		

Sample conditions:

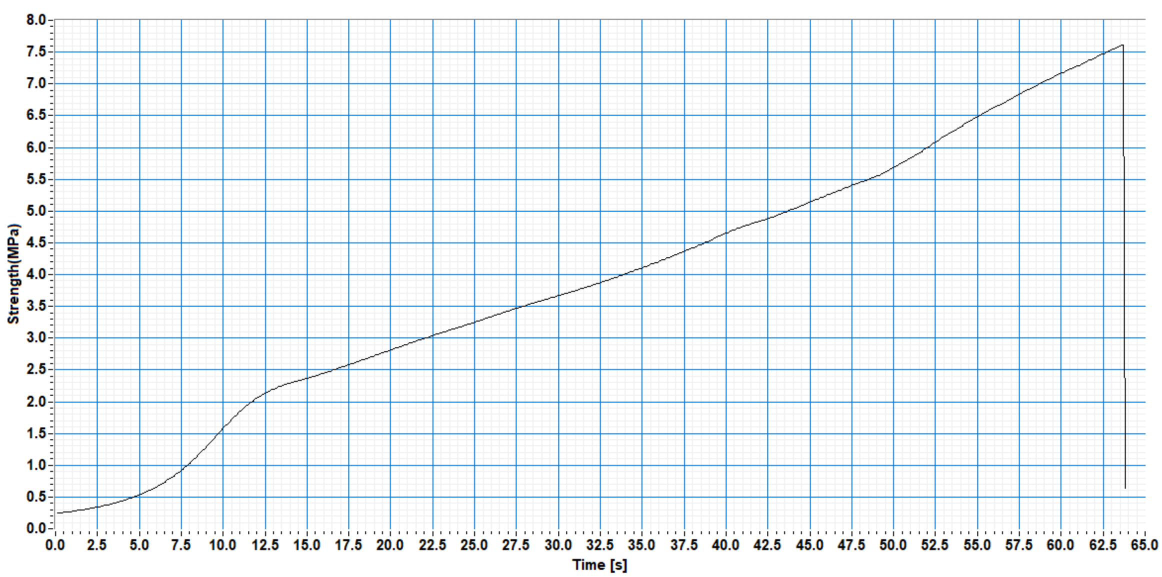
Curing Time : 28 Days

Specimen ID : 2

Dimensions	: b(mm) 40.00	h(mm) 40.00	l(mm) 160.00		
Area [mm2]	: 426.7	:		Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 45.212	Test date	: 03/26/20 - 16:26		

Max Load [kN] : 3.25 **Strength [MPa] : 7.62**

Notes :



Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 1-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 1-3		
Specimen type	: Beam	Admixture 2	: Sika control NS
Admixture 1	: Sika Viscocrete 2100		

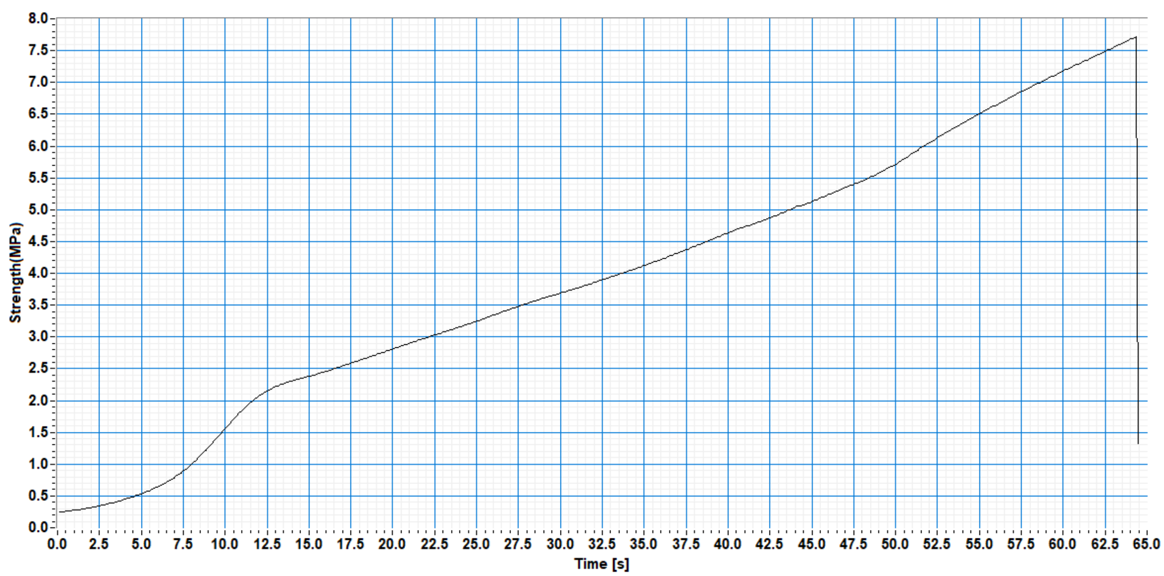
Sample conditions:

Curing Time	: 28 Days
Specimen ID	: 3

Dimensions	: b(mm) 40.00	h(mm)	40.00	l(mm)	160.00
Area [mm2]	: 426.7		:	Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 45.288	Test date			: 03/26/20 - 16:26

Max Load [kN] **: 3.29** **Strength [MPa]** **: 7.72**

Notes :



Syracuse University

Flexural tests on beams: EN 196-1

Mix No. : Mix 1-4
Testing machine : CONTROLS - Automax
Client : Syracuse University
Reference : Mix 1-4
Specimen type : Beam
Admixture 2 : Sika control NS
Admixture 1 : Sika Viscocrete 2100

Sample conditions:

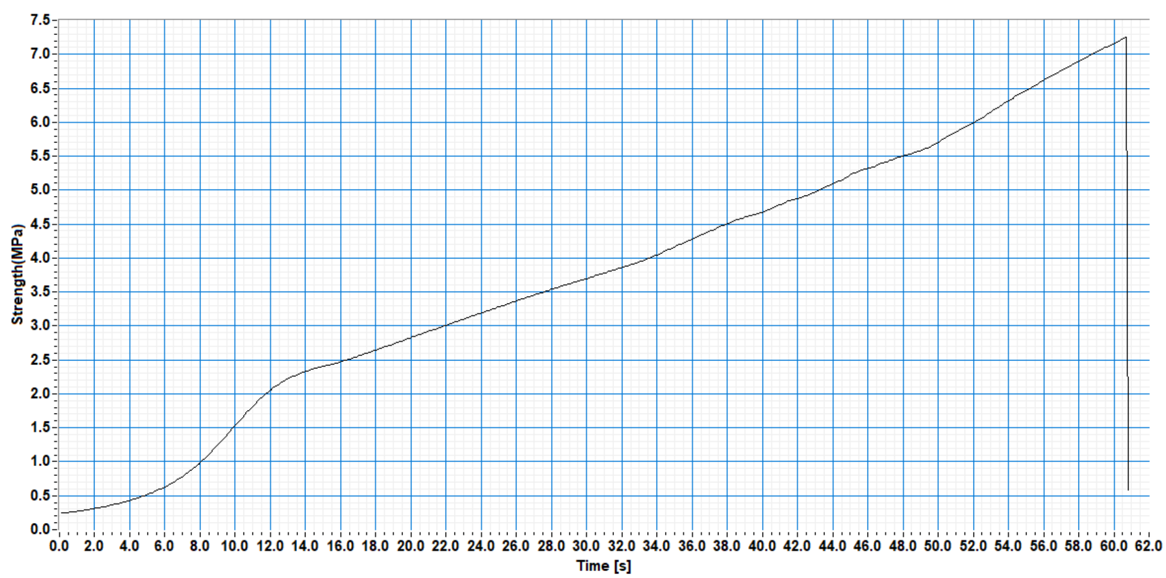
Curing Time : 28 Days

Specimen ID : 1

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00
Area [mm2] : 426.7 : Mass [Kg] : 0.000
No of upper rollers : 1 "L" distance [mm] : 100.0 Specimen age [gg] : 28 days
Load Rate(N/s) : 44.665 Test date : 03/26/20 - 16:26

Max Load [kN] : 3.09 Strength [MPa] : 7.25

Notes :



Test Report A.47 Bending Strength Report – Mix 1-4

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 1-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 1-4		
Specimen type	: Beam	Admixture 2	: Sika control NS
Admixture 1	: Sika Viscocrete 2100		

Sample conditions:

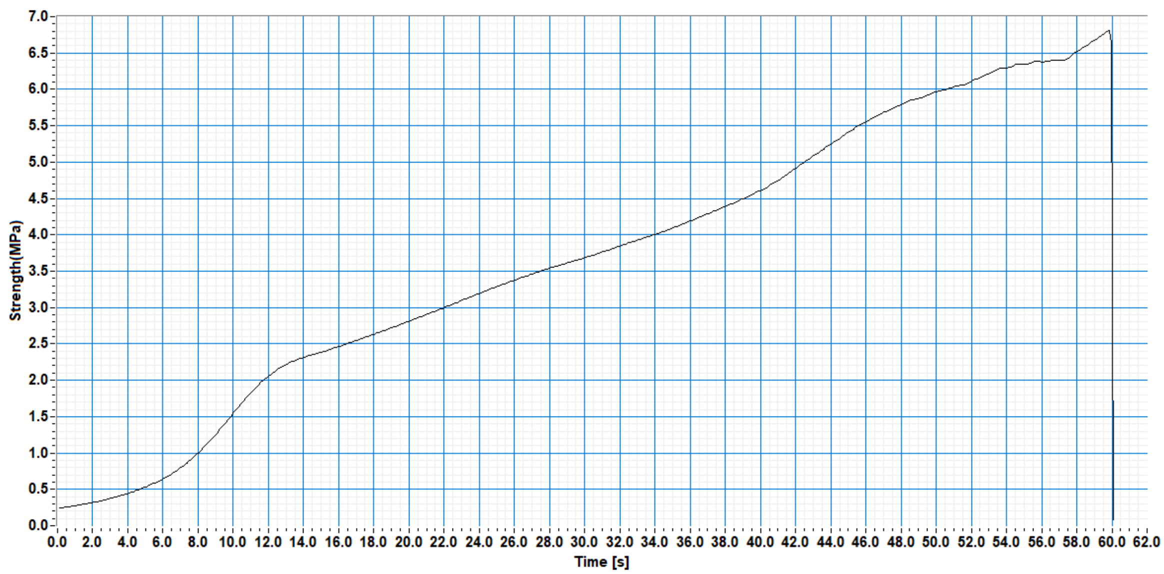
Curing Time : 28 Days

Specimen ID : 2

Dimensions	: b(mm) 40.00		h(mm) 40.00		l(mm) 160.00		
Area [mm2]	: 426.7		:		Mass [Kg]	:	0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0		Specimen age [gg]	:	28 days
Load Rate(N/s)	: 41.274		Test date		: 03/26/20 - 16:26		

Max Load [kN] : 2.91 **Strength [MPa] : 6.81**

Notes :



Test Report A.48 Bending Strength Report – Mix 1-4

Syracuse University

Flexural tests on beams: EN 196-1

Mix No. : Mix 1-4

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 1-4

Specimen type : Beam

Admixture 2 : Sika control NS

Admixture 1 : Sika Viscocrete 2100

Sample conditions:

Curing Time : 28 Days

Specimen ID : 3

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00

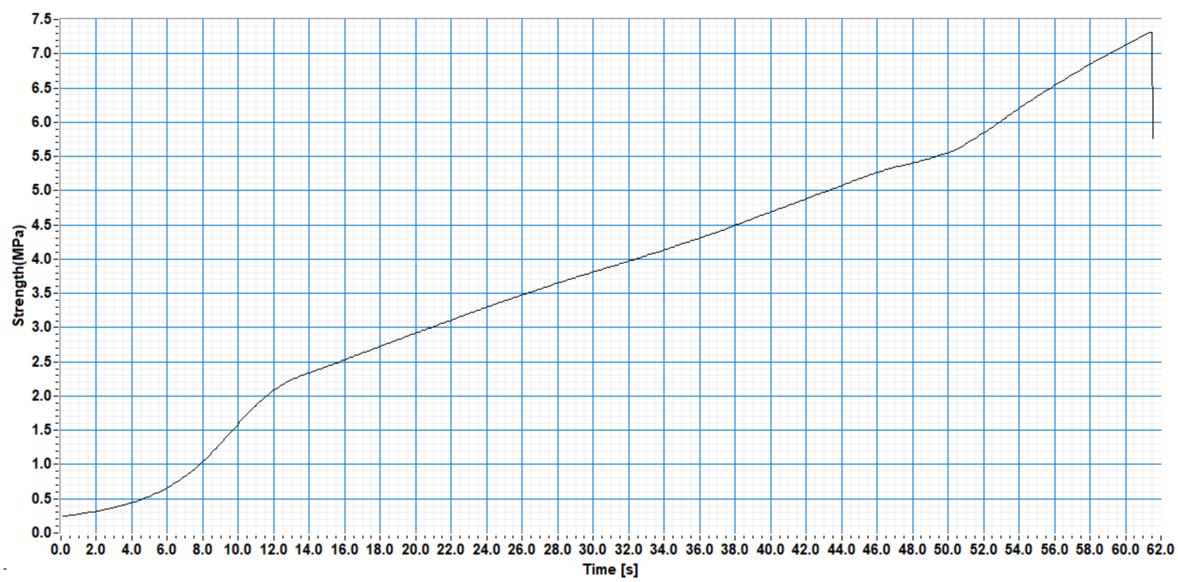
Area [mm2] : 426.7 : Mass [Kg] : 0.000

No of upper rollers : 1 "L" distance [mm] : 100.0 Specimen age [gg] : 28 days

Load Rate(N/s) : 44.076 Test date : 03/26/20 - 16:26

Max Load [kN] : 3.12 **Strength [MPa] : 7.32**

Notes :



Test Report A.49 Bending Strength Report – Mix 2-3

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 2-3
Testing machine	: CONTROLS - Automax
Client	: Syracuse University
Reference	: Mix 2-3
Specimen type	: Beam
Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

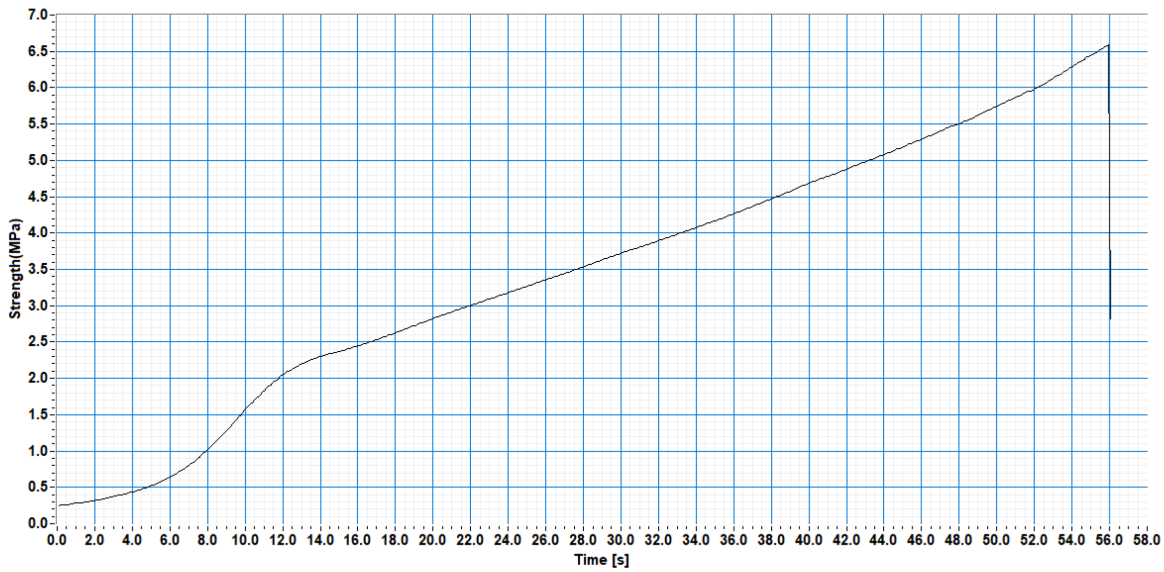
Specimen ID : 1

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00

Area [mm2]	: 426.7		:	Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 43.537	Test date		: 03/26/20 - 16:26	

Max Load [kN] : 2.81 **Strength [MPa] : 6.59**

Notes :



Test Report A.50 Bending Strength Report – Mix 2-3

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 2-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-3		
Specimen type	: Beam	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

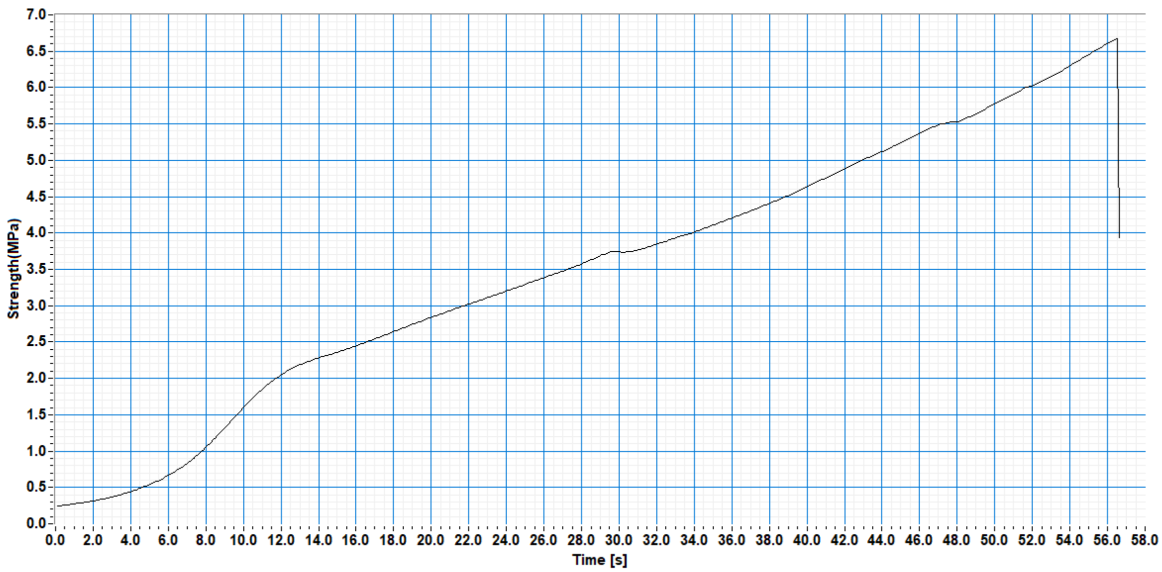
Curing Time : 28 Days

Specimen ID : 2

Dimensions	:	b(mm) 40.00		h(mm) 40.00		l(mm) 160.00	
Area [mm2]	: 426.7		:		Mass [Kg]	: 0.000	
No of upper rollers	: 1	"L" distance [mm]	: 100.0		Specimen age [gg]	: 28 days	
Load Rate(N/s)	: 43.578		Test date		: 03/26/20 - 16:26		

Max Load [kN] : 2.85 **Strength [MPa] : 6.68**

Notes :



Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 2-3
Testing machine	: CONTROLS - Automax
Client	: Syracuse University
Reference	: Mix 2-3
Specimen type	: Beam
Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

Specimen ID : 3

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00

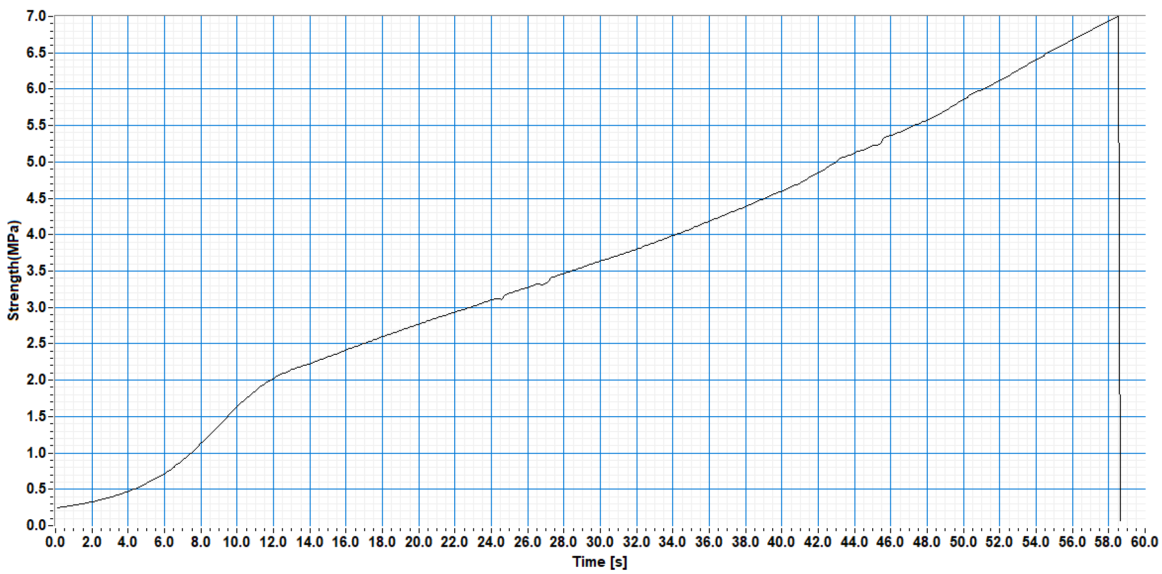
Area [mm2] : 426.7 : Mass [Kg] : 0.000

No of upper rollers : 1 "L" distance [mm] : 100.0 Specimen age [gg] : 28 days

Load Rate(N/s) : 45.181 Test date : 03/26/20 - 16:26

Max Load [kN] : 2.98 **Strength [MPa] : 7.00**

Notes :



Test Report A.52 Bending Strength Report – Mix 2-4

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 2-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-4		
Specimen type	: Beam	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

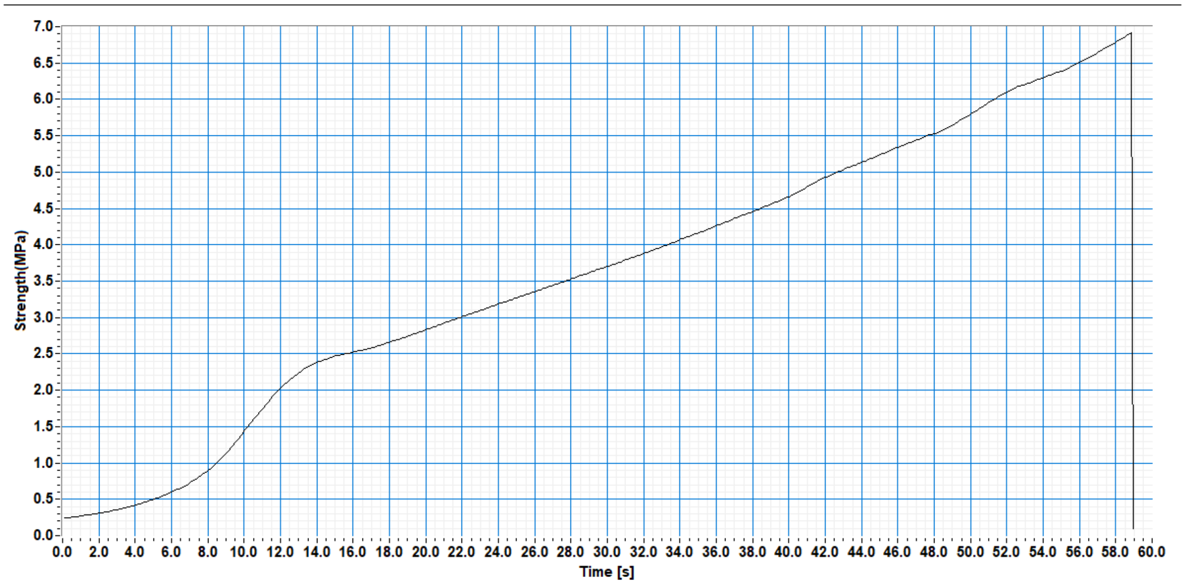
Curing Time : 28 Days

Specimen ID : 1

Dimensions	: b(mm) 40.00	h(mm) 40.00	l(mm) 160.00		
Area [mm2]	: 426.7	:		Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 43.728	Test date	: 03/26/20 - 16:26		

Max Load [kN] : 2.95 **Strength [MPa] : 6.92**

Notes :



Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 2-4
Testing machine	: CONTROLS - Automax
Client	: Syracuse University
Reference	: Mix 2-4
Specimen type	: Beam
Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

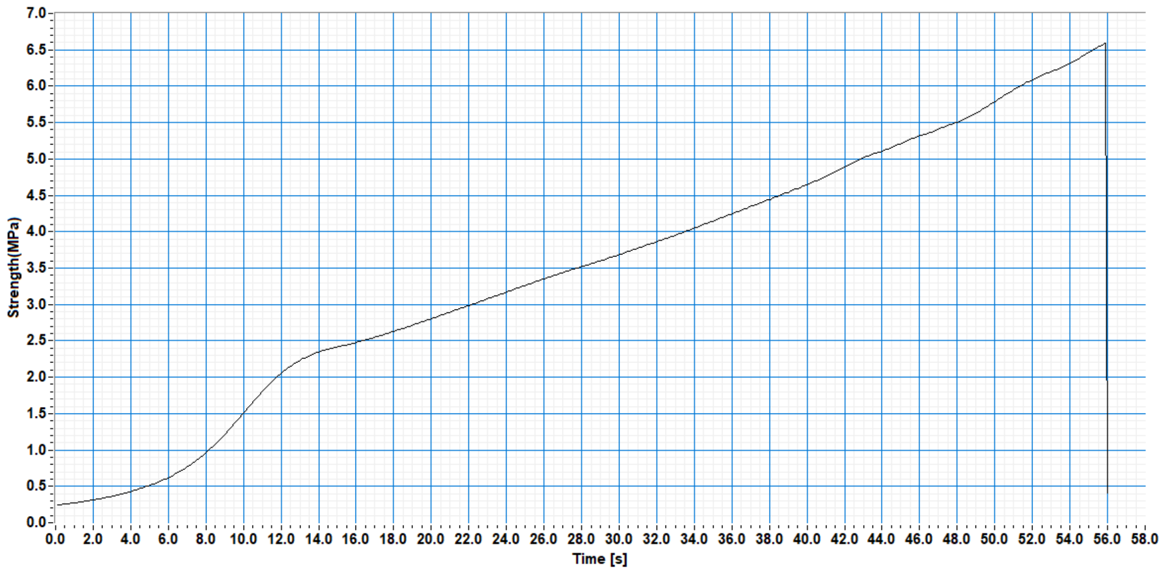
Specimen ID : 2

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00

Area [mm2]	: 426.7		:	Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 44.351	Test date	: 03/26/20 - 16:26		

Max Load [kN] : 2.81 **Strength [MPa] : 6.59**

Notes :



Test Report A.54 Bending Strength Report – Mix 2-4

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 2-4		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 2-4		
Specimen type	: Beam	Admixture 2	: MasterLife CRA 007
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

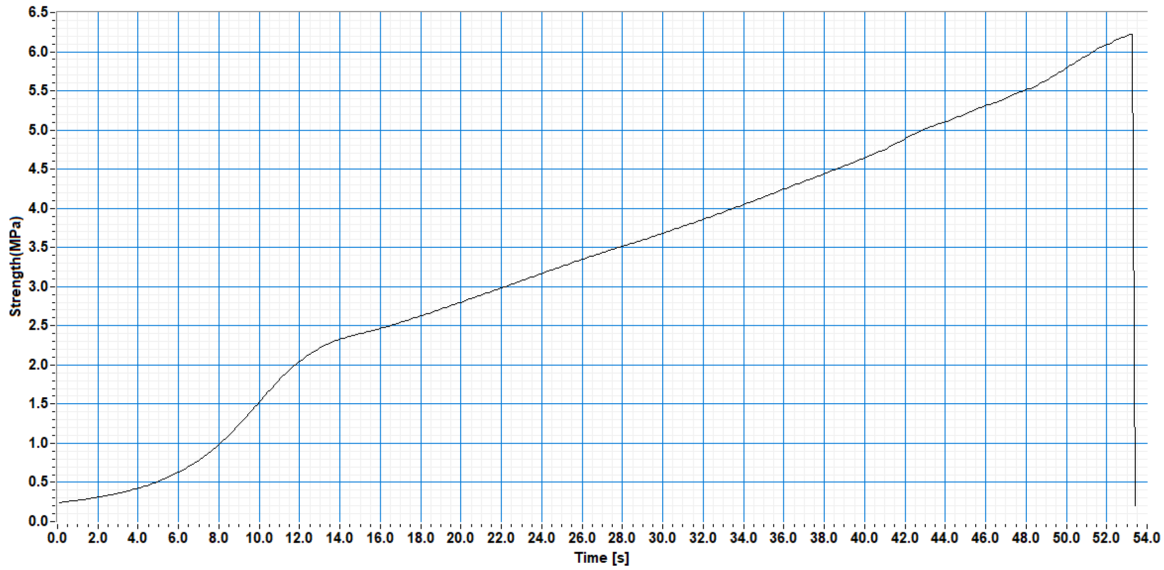
Curing Time : 28 Days

Specimen ID : 3

Dimensions	: b(mm) 40.00		h(mm) 40.00		l(mm) 160.00		
Area [mm2]	: 426.7		:		Mass [Kg]	:	0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0		Specimen age [gg]	:	28 days
Load Rate(N/s)	: 44.620		Test date		: 03/26/20 - 16:26		

Max Load [kN] : 2.66 **Strength [MPa] : 6.23**

Notes :



Test Report A.55 Bending Strength Report – Mix 3-3

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 3-3
Testing machine	: CONTROLS - Automax
Client	: Syracuse University
Reference	: Mix 3-3
Specimen type	: Beam
Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

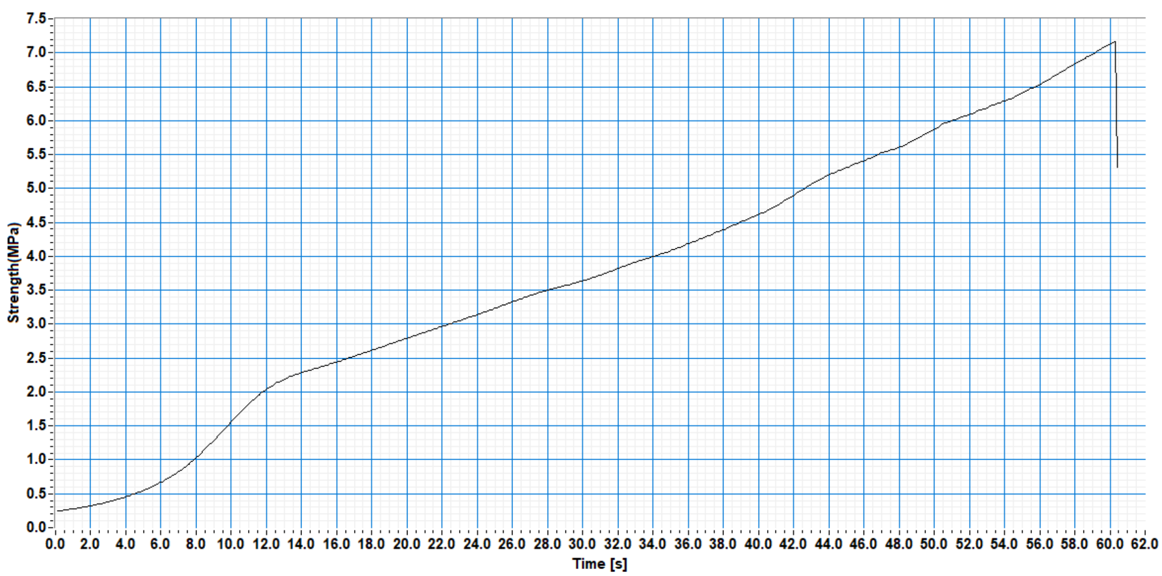
Specimen ID : 1

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00

Area [mm2]	: 426.7		:	Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 44.145	Test date	: 03/26/20 - 16:26		

Max Load [kN] : 3.06 Strength [MPa] : 7.16

Notes :



Test Report A.56 Bending Strength Report – Mix 3-3

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 3-3
Testing machine	: CONTROLS - Automax
Client	: Syracuse University
Reference	: Mix 3-3
Specimen type	: Beam
Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620

Sample conditions:

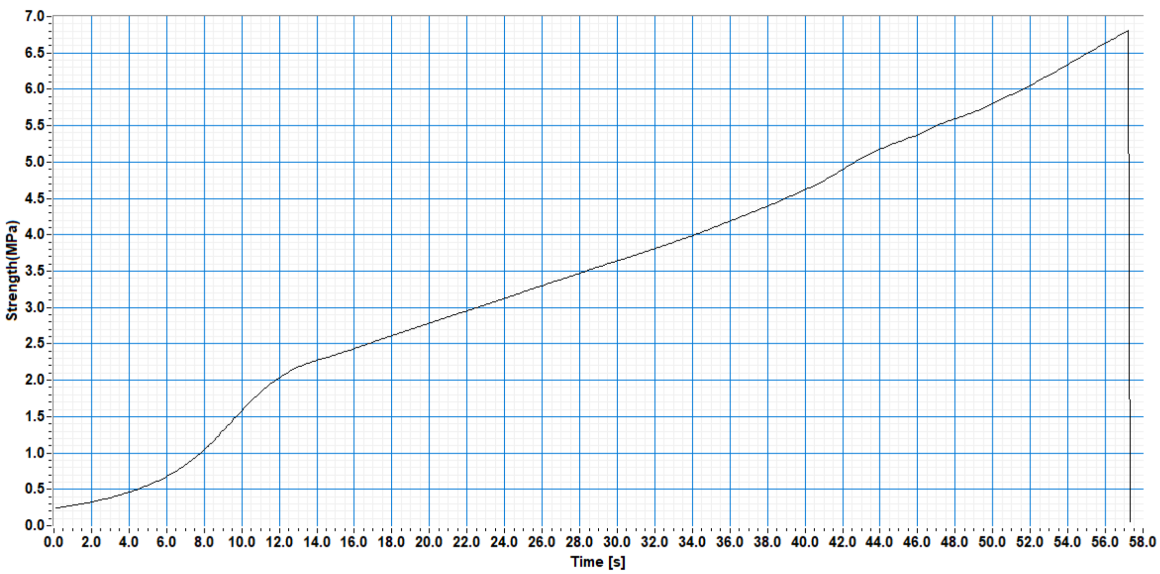
Curing Time : 28 Days

Specimen ID : 2

Dimensions	: b(mm) 40.00	h(mm) 40.00	l(mm) 160.00		
Area [mm2]	: 426.7	:		Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 44.354	Test date	: 03/26/20 - 16:26		

Max Load [kN] : 2.90 **Strength [MPa] : 6.81**

Notes :



Test Report A.57 Bending Strength Report – Mix 3-3

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 3-3		
Testing machine	: CONTROLS - Automax		
Client	: Syracuse University		
Reference	: Mix 3-3		
Specimen type	: Beam	Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620		

Sample conditions:

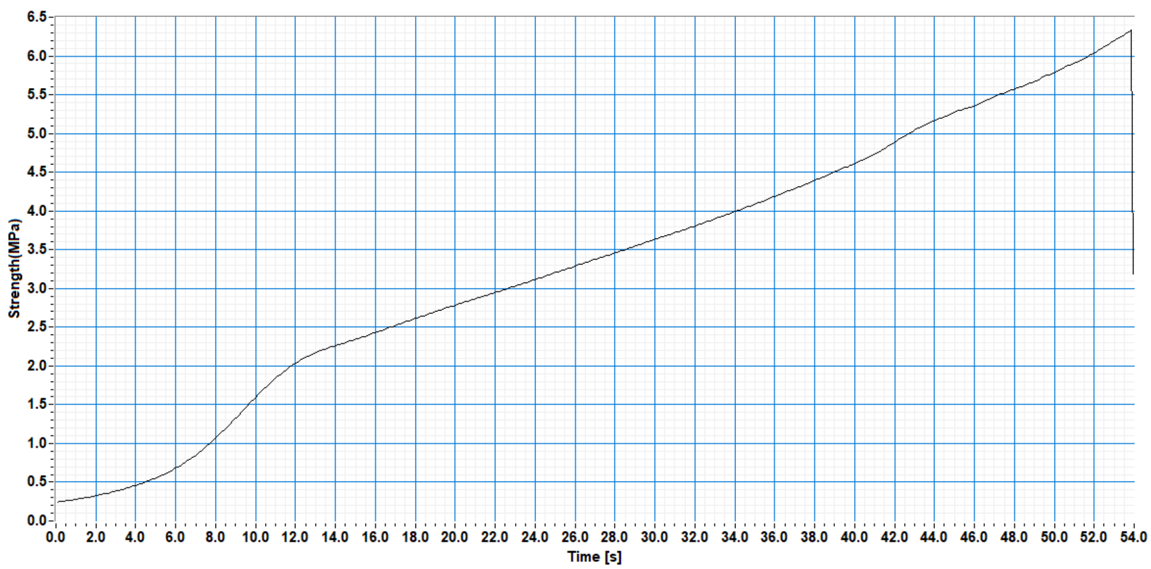
Curing Time : 28 Days

Specimen ID : 3

Dimensions	: b(mm) 40.00		h(mm) 40.00		l(mm) 160.00		
Area [mm2]	: 426.7		:		Mass [Kg]	:	0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0		Specimen age [gg]	:	28 days
Load Rate(N/s)	: 43.681		Test date		: 03/26/20 - 16:26		

Max Load [kN] : 2.70 **Strength [MPa] : 6.33**

Notes :



Test Report A.58 Bending Strength Report – Mix 3-4

Syracuse University

Flexural tests on beams: EN 196-1

Mix No.	: Mix 3-4
Testing machine	: CONTROLS - Automax
Client	: Syracuse University
Reference	: Mix 3-4
Specimen type	: Beam
Admixture 2	: MasterLife SRA 035
Admixture 1	: BASF MasterGlenium 7620

Sample conditions:

Curing Time	: 28 Days

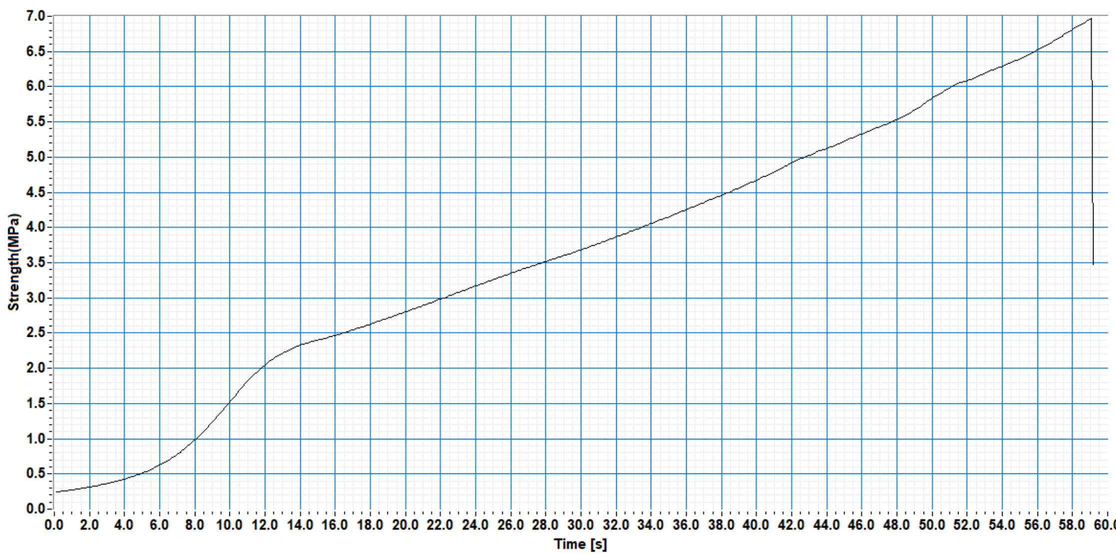
Specimen ID	: 1

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00

Area [mm2]	: 426.7		:	Mass [Kg]	: 0.000
No of upper rollers	: 1	"L" distance [mm]	: 100.0	Specimen age [gg]	: 28 days
Load Rate(N/s)	: 43.581	Test date			: 03/26/20 - 16:26

Max Load [kN] **: 2.98** **Strength [MPa]** **: 6.97**

Notes :



Test Report A.59 Bending Strength Report – Mix 3-4

Syracuse University

Flexural tests on beams: EN 196-1

Mix No. : Mix 3-4

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 3-4

Specimen type : Beam

Admixture 2 : MasterLife SRA 035

Admixture 1 : BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

Specimen ID : 2

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00

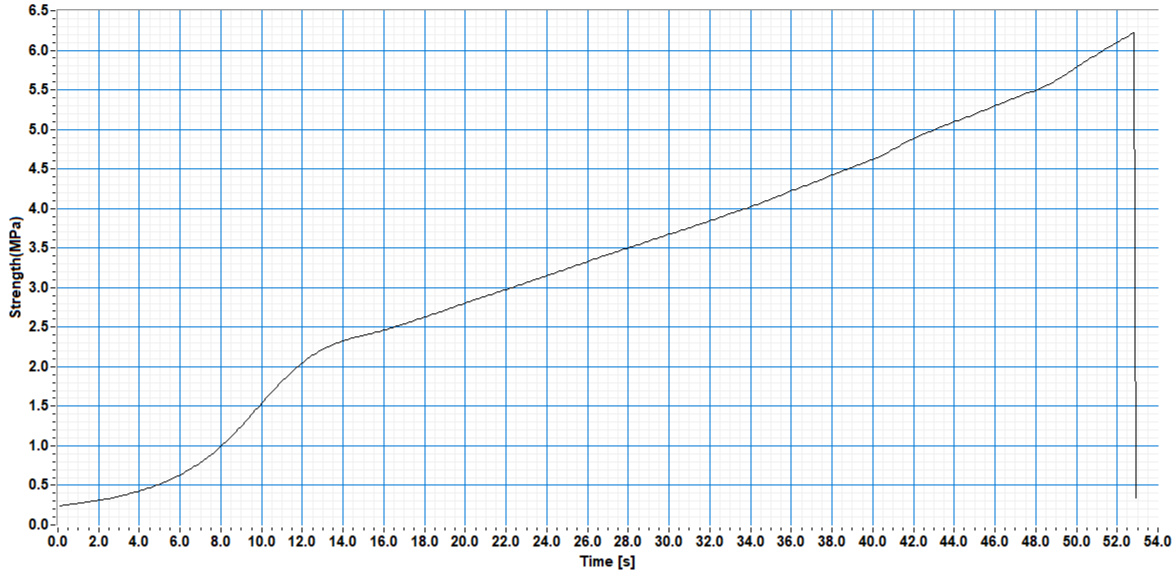
Area [mm2] : 426.7 : Mass [Kg] : 0.000

No of upper rollers : 1 "L" distance [mm] : 100.0 Specimen age [gg] : 28 days

Load Rate(N/s) : 44.400 Test date : 03/26/20 - 16:26

Max Load [kN] : 2.65 Strength [MPa] : 6.22

Notes :



Syracuse University

Flexural tests on beams: EN 196-1

Mix No. : Mix 3-4

Testing machine : CONTROLS - Automax

Client : Syracuse University

Reference : Mix 3-4

Specimen type : Beam

Admixture 2 : MasterLife SRA 035

Admixture 1 : BASF MasterGlenium 7620

Sample conditions:

Curing Time : 28 Days

Specimen ID : 3

Dimensions : b(mm) 40.00 h(mm) 40.00 l(mm) 160.00

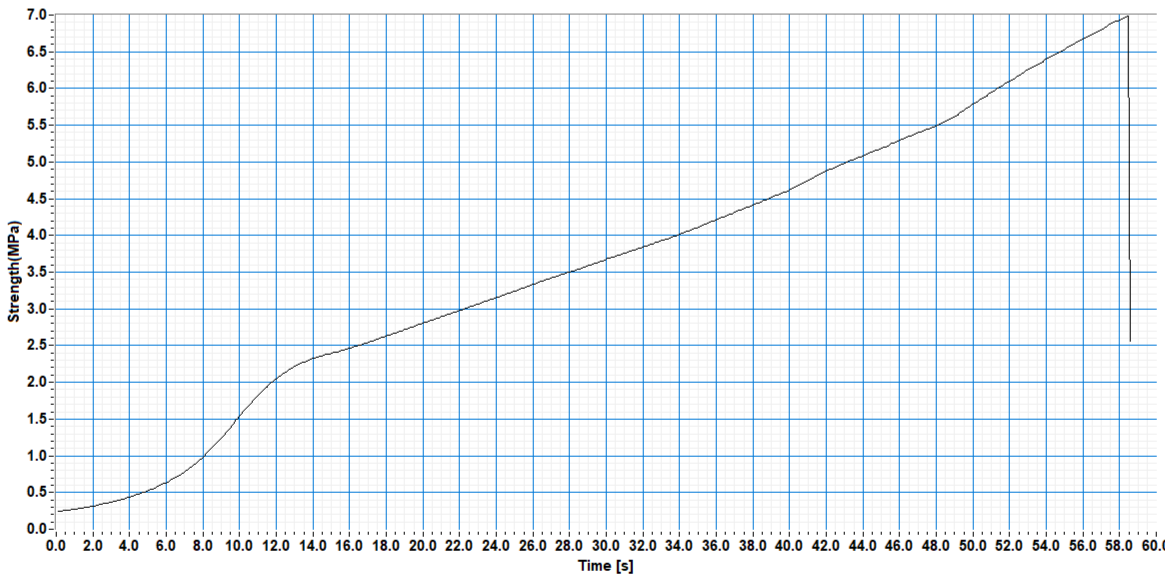
Area [mm2] : 426.7 : Mass [Kg] : 0.000

No of upper rollers : 1 "L" distance [mm] : 100.0 Specimen age [gg] : 28 days

Load Rate(N/s) : 44.965 Test date : 03/26/20 - 16:26

Max Load [kN] : 2.98 Strength [MPa] : 6.99

Notes :



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VITA

RAED ASHOUR

Education

Syracuse University, NY, USA

College of Engineering & Computer Science Aug. 2018 – June 2020

- M.Sc. Civil Engineering (3.95/4)

Maxwell School of Citizenship and Public Affairs. Aug. 2018 –June 2020

- Certificate of Advanced Study in Public Infrastructure Management and Leadership (GPA: 3.66/4)

Maxwell School of Citizenship and Public Affairs. Aug. 2018 – Dec. 2019

- Certificate of Advanced Study in Public Administration (GPA: 3.83/4)

Indiana University, Kelley School of Business, IN, USA June 2015 – Aug. 2015

- Intensive summer school with focus on Business Management and Entrepreneurship

The Islamic University, Palestine Sep. 2011 – Dec. 2015

- B.Sc. Civil Engineering (85.07%)

HONORS AND AWARDS

Fulbright Foreign Student Program, Syracuse, NY July 2018 – Aug. 2020

- A scholarship sponsored by the US Department of State
- The program enables graduate students, young professionals and artists to study and conduct research in the United States

The Global Business Institute Scholarship, USA June 2015 – Aug. 2015

- A scholarship sponsored by the US Department of State and the Coca-Cola Company
- Funded my participation in the management and entrepreneurship summer school at Indiana University
- A highly competitive scholarship in which 100 students from MENA region were selected from more than 6,000 applicants

HQSF Scholarship, Palestine Sep. 2011 – Dec. 2015

- A scholarship that funded my undergraduate study

RESEARCH

Shrinkage Cracks Developed in Cement Mortar Lined Pipes Dec. 2018 – June 2020

- The research aims to develop a low shrinkage cement mortar mix that can be used in lining large water pipes
- A funded research project by Raymond Intl. for Integrated Pipeline Services in Saudi Arabia

Coastal Water Quality Monitoring Using Remote Sensing Jan. 2015 – Jan. 2016

- The research aimed to develop an algorithm that can be used to detect sea water quality using satellite images
- The research was funded by The Ministry of Environmental Affairs Palestine

EXPERIENCE

Department of Civil Engineering, Syracuse University, NY, USA Dec. 2018 – June 2020

Research Assistant

- Researching the shrinkage micro-cracks that develop in cement mortar lined pipes
- Developing a new cement mortar mix with high strength and low shrinkage properties

Rifaq Contracting Company (RCC), Rawabi City, Palestine Dec. 2017 – June 2018

Project Engineer

- Managed the finishing works of four towers in the 4th neighborhood in Rawabi City

Bayti Real Estate Investment Company, Rawabi City, Palestine July 2016 – Dec. 2017

Site Engineer

- Inspected the 3rd neighborhood infrastructure and landscape project
- Was part of various finishing works projects in the Commercial Center of Rawabi City; the projects included but not limited to Hugo Boss, Mango, Massar Company, Connect Company, American Eagle, Estee Lauder, and Siroter Café

Tabaria L.T.D (Fixed-term employment contract)**,** Gaza, Palestine Sep. 2015 – July 2016

Site Engineer

- Inspected the maintenance and rehabilitation of the UN schools