B.Sc. in Civil Engineering

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RELATIONSHIP BETWEEN ULTRASONIC PULSE VELOCITY AND COMPRESSIVE STRENGTH OF CONCRETE FOR DIFFERENT TYPES OF AGGREGATE AVAILABLE IN BANGLADESH

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The thesis titled “Relationship between Ultrasonic Pulse Velocity and Compressive Strength of Concrete for Different Types of Aggregate Available in Bangladesh” submitted by Md. Nafiur Rahman and Md. Tanveer Hasan, St. No. 115441, 105404 has been found as satisfactory and accepted as partial fulfillment of the requirement for the Degree Bachelor of Science in Civil Engineering.

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We hereby declare that the undergraduate research work reported in this thesis has been performed by us under the supervision of Professor Dr. Tarek Uddin and this work has not been submitted elsewhere for any purpose (except for publication).

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DEDICATION

We dedicate our thesis work to our family. A special feeling of gratitude to our loving parents.

We also dedicate this thesis to our many friends who have supported us throughout the process. We will always appreciate all they have done.

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ABSTRACT

Keywords: Ultrasonic Pulse Velocity, compressive strength, coarse aggregate, sand to aggregate ratio, non-destructive test, steel slag etc.

For quite a few years, many attempts are made in order to find a suitable relationship between ultrasonic pulse velocity (UPV) and compressive strength of concrete. Such relations, if properly established, can promote a sustainable structural health monitoring system. Therefore, in this study, different types of aggregate that are commonly available in Bangladesh are tested in order to find a working relationship between UPV and compressive strength of concrete. Tests have been carried out on 7, 28, 60 and 90 days. Three volumetric sand to total aggregate ratios (s/a) 0.36, 0.40, 0.44 are considered to study the effect of variation of s/a. And, three W/C ratio are chosen as 0.45, 0.50, 0.55. The cement paste occupies 32% of the total concrete volume (V_{Paste} =32%). For some cases, volumetric mix ratios of 1:1.5:3 and 1:2:4 were also prepared in order to relate to the common field practice.

Here, the compressive strength of concrete is related with UPV on the basis of s/a ratio variation. Some relationships are proposed between UPV and compressive strength. The possibility of relationship between Young's modulus of concrete and UPV is also explored. Another part of the study was to find out the suitability of steel slag as a coarse aggregate for construction purpose. Different steel slag aggregates were tested for aggregate properties. Also, the behavior of UPV on concrete made with steel slag was found out to take a comprehensive study. Finally, an elaborate and comprehensive analysis is made in order to compare between concrete made with different aggregates to have a final view about the relationship between ultrasonic pulse velocity (UPV) and compressive strength of concrete.

LIST OF SYMBOLS

V_p	Pulse velocity of concrete
S	Compressive strength of concrete
V_p-S	Relationship between ultrasonic pulse velocity and compressive strength of concrete
W/C	Water to Cement ratio
s/a	Sand to total aggregate volumetric ratio
V_{paste}, %	Volumetric cement paste content
R^2	Pearson product moment correlation co-efficient
f'_c	Compressive strength of concrete
f_t	Tensile strength of concrete
E_c	Young’s Modulus of concrete

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Chapter 1 Introduction

1.1 General

The compressive strength of concrete has always been considered as one of the most important properties of concrete. In structures, its primary application is to resist compressive stress. Its strength, however, is defined as its resistance to rupture and can be measured from its strength in compression, in tension or in shear or flexure. Hence, to design for a structure, determination of compressive strength is crucial. A number of methods are widely used to determine the strength of concrete.

The goal of all these methods is to find out the most effective strength for design purpose. There are theoretical and practical methods. Theoretical methods like the classic law of Abram's [1] or Powers and Brownyard [2] relationship can give the compressive strength just by considering W/C ratio, volume of cement or specific volume of cement and some other strength regarding factors. This way, the strength determination does not get time consuming and also good for 28 days strength if the concrete is fully compacted. Although in practical situation, the compressive strength is found out to be much lower than theoretically estimated.

This is because of the consideration of concrete to be a homogenous and fully solid mass. In actual scenario, there are always flaws present in the concrete structures. They can be like voids due to less degree of compaction, bleeding channels or ruptures due to drying and temperature shrinkage. Griffith's theory explains that, due to presence of flaws, concrete undergoes a considerable reduction in its strength. Mostly because of the intense stress concentration in or around the voids. So, the practical methods are carried out in order to determine the actual strength of concrete.

The compressive strength of concrete is usually determined by testing cylinders or cubes made in laboratory. These tests are referred as destructive tests as the concrete will be crushed and no longer usable. The drawbacks of these methods are, they generate a lot of rubbish and also cannot ensure the quality of concrete in actual structures. Destructive tests are also cannot be held to inspect the structural health in any instance thus limiting the scope for continuous monitoring the state of the structure.

Hence the use of non-destructive methods can be adopted. Non-destructive tests are the methods to find out the compressive strength of concrete without crushing any concrete build. Concrete in service is exposed to a wide variety of environment and due its physical and chemical nature it may deteriorate inside [3]. Non-destructive tests response to the extent of impairment. Furthermore, in order to assess current adequacy and future performance, routine evaluation of structural health is a primary concern [4]. In these regard, non-destructive tests are capable of assessing structures and call for remedial measures if necessary.

Among the non-destructive tests, four are usually performed:

i) Impact-echo method

ii) Ultrasonic pulse velocity method

iii) Impact elastic wave method

iv) Thermographic method (used to find flaws in concrete)

In this thesis, **Ultrasonic pulse velocity** method will be focused in order to determine the compressive strength of concrete. The effect of various strength regarding factor such as mix proportion, aggregate, water-content and age on ultrasonic pulse velocity will be studied. Therefore, necessary numerical and graphical expressions will be established for predicting the compressive strength of concrete.

1.2 Literature Review

In order to find the most suitable and fit correlation between pulse velocity (V_p) and strength of concrete (S), many researchers tried to find the parameters that effect both the velocity and strength to build V_p-S standard correlation. In the attempt, many parameters were chosen to study to see their effect on V_p and S. Some of these parameters and their studies are discussed in this literature review.

1.2.1 Water Content (W/C)

Water content plays a vital role in the context of gaining strength and pulse velocity. W/C and age of concrete can be can considered as ruling parameter to find out V_p-S relationship as done in a study led by I. Lawson et al (2011) [5]. In that study, the ranges of W/C considered were 0.35, 0.40, 0.50, 0.60, and 0.75. Based on these four different W/C, UPV measurement and compressive strength tests were carried out at the age of 2, 7, 15 and 28 days. Pulse velocity at the age of 28-days for W/C of 0.40 and 0.75 were around 4600 m/s and 4200m/s respectively. So, it was observed that with higher W/C the pulse velocity of concrete gets lower. Similar trend was observed to be followed by the strength of concrete with W/C. Compressive strength at the age of 28-days for W/C of 0.40 and 0.75 were around 37MPa and 22MPa respectively. So it was concluded that higher W/C creates more voids and less mass. Velocity can only get higher if there are more solid mass present. Lower W/C creates dense concrete so velocity and strength both were supposedly found higher for 28-day measurement. Then the V_p-S curve was established for four distinct W/C and regression analysis were done to find out four compressive strength equations. V_p-S relation shows that with higher velocity strengths tend to be higher. Their Pearson coefficient of determination, R^2 were 0.866, 0.981, 0.888, 0.994 and 0.989 for W/C 0.35, 0.40, 0.50, 0.60, and 0.75 respectively. They were all close to 1 indicating high relevance between data points and the regression curves. Another study by Y. Lin et al (2007) [6] shows the variance in strength for W/C of 0.3, 0.4, 0.5, 0.6, and 0.7. Researchers in this study prepared fifteen mix proportions considering five different W/C. In the study they examined the cement paste and concrete side by side. They showed that from higher to lower W/C, both the cement paste and concrete gain strength and pulse velocity. But it was also observed that both the cement paste and concrete has compressive strength around 11000 psi. Although, the curves were almost parallel and there were significant gap (around 1000m/s) between their respective UPV values. Cement paste had far less UPV than concrete. The reason behind was explained as the strength of concrete is as good as the strength of the cement paste. For a particular W/C concrete and cement paste must reach the same strength. Adding aggregate may increase the UPV of concrete but it has less significance upon its strength.

1.2.2 Age

Age is one of the most fundamental parameter on which the strength and UPV both relies on. It has been established that both strength and UPV of concrete grows gradually with aging of concrete. With age concrete matures, solid mass develops with hydration. Solid mass yields the desired strength and UPV also shows the effect of it. I. Lawson et al (2011) [5] showed in the study that, concrete specimen cured in water at 20^{o}C (68^{o}F) and tested at 2, 7, 15, and 28 days reveals that concrete (18% paste content) with high W/C (W/C = 0.75) at the age of 2 days has a UPV of about 89% of that of 28 days, but the strength is only about 60%. Also, at the age of 2 days, concrete with low W/C (W/C = 0.35) has a UPV that is approximately 97% of that at 28 days and the strength is about 30%. To sum up, the UPV and strength growth rates of high and low W/C concrete are significantly different at an early age. In order to predict strength accurately, it was proposed in that study to eliminate the interference caused by the different UPV and strength growth rates at early ages.

Another Study by Y. Lin et al (2007) [6] backs up the above finding. To see the effect of age over W/C, test cylinders were cured in water at 20^{o}C and tested at 1, 3, 7, 14, and 28 days. Two distinct mix proportions were considered over W/C of 0.7 and 0.3.

It was observed that concrete with a high W/C at the ages of 1 and 3 days has a UPV that is 80 and 90% of that at the age of 28 days, but the strength only grows 25% and 45%, respectively. Also, at the age of 1 and 3 days, concrete with low W/C has a UPV that is 90% and 95% of that at 28 days and the strength grows to 55% and 80%, respectively. The study proposed that it is better to separately consider the effects of age and mixture proportion on the UPV and strength relationship.

David A. Anderson & Roger K. seals (1981) [7] conducted a study based on two phases. In phase-I, Compressive, split tensile, and flexural strength tests were performed at 2, 7, 28, and 90 days. Coefficient of variation (CV) was introduced to indicate the relative variability of the different test measurements. As the means for compressive and tensile strength differ by an order of magnitude, CV was used to compare the variability. And it backs up the other studies that showed an interference of measurements in early ages. This study also showed an interference in terms of higher coefficient of variation for pulse velocity at 1-day.

1.2.3 Aggregate & Mix Proportion

Aggregates have a serious effect on pulse velocity. For different type of aggregate and mix proportions pulse velocity changes a lot and thus needed to be specified. The materials I. Lawson et al (2011) [5] used in the study for making specimen include ordinary Portland Limestone type 2.5N, standard sand, Coarse Aggregate (CA) of 10 mm grain size. Their mix proportion was 1:2:4 and for each W/C they used 15.4Kg of cement, 30.9Kg of sand and 61.7Kg of CA. Highest V_p was found out to be 4600 m\s. And the result include high determination for predicting strength indicating quality of concrete in terms of density, homogeneity and uniformity was good.

Y. Lin et al (2007) [6] showed that aggregate could be a key factor to predict compressive strength of concrete. They considered detail specification and measurement for materials including cement, fine aggregate (FA), course aggregate and water. Collected from same source, river sand with a saturated-surface dry (SSD) density of 2.62 and crushed stone with an SSD density of 2.60 were used as fine and coarse aggregates, respectively. Upon completing sieve analysis fine aggregates were found to be uniformly graded and course aggregate to be well graded. The pulse velocity were found out to be 4960 m/s and 5100 m/s for FA and CA respectively. Fifteen mixture content were prepared for the test. For assessing the mix proportions, seven of them were plotted into a single graph yielding the basic shape of V_p-S relationship coinciding with one another. Also, three data points from each of fifteen mix proportions combining 45 data points of 28-day strength were also plotted in graph to establish V_p-S relationship. But ambiguities were found in the plot as it was a scattered distribution with serious errors. The Pearson coefficient of determination was 0.84 thus concluding that it cannot correlate the strength-velocity relationship. Thus the study proposed a new approach considering CA content to be a ruling factor for establishing V_p-S relationship to predict strength for hardened concrete. For fifteen mix proportions, CA content was considered in three group (1165, 915, and 666 kg/m3). Again a graph was plotted for these three groups of CA content which include fifteen mix proportion for five W/C. Three curves were plotted for three groups of CA considering 28-day strength. The plot showed that these three CA content curves were almost parallel. For concrete with a high W/C (0.7), UPV of hardened concrete does not change significantly when CA content changes from 666 to 1165 kg/m^3, but the strength of hardened concrete decreases with an increase in CA content. For concrete with a low W/C (0.3), UPV increases slightly (approximately 2%) with more CA content, but the strength decreases. Another graph plotted considering UPV and CA contents to be vertical and horizontal components indicated that UPV has less influence on concrete of high W/C (0.7) followed by a CA content change. When the W/C of concrete is low, UPV increases less than 2% with the increase of CA content. Another plot of strength-CA content showed the change of strength of five W/C in different CA contents. The strength-CA content also indicated that with a certain W/C, concrete strength increases with the increase of s/a (sand-aggregate ratio, meaning lower CA content). The study reveals that concrete with either high or low W/C shows same result indicating with lower CA content comes higher FA content, resulting in compactness as well as strength in hardened concrete. The earlier V_{p}-S curves for three groups of CA contents showed that as CA content varies for concrete with a high W/C (0.7), the strength of hardened (28-day) concrete changes considerably, but pulse velocity remains almost the same. On the other hand, pulse velocity for concrete of low W/C increases as CA content increases but strength decreases. The study proposed that, in order to establish V_p-S relation equation for predicting strength for hardened concrete, CA content must be mentioned for right prediction.

1.2.4 Air Content

Seals, Roger K., and Anderson, David A. (1981) [7] considered air content to be an important parameter regarding strength of concrete. They considered some well controlled mixtures and tested them for pulse velocity and strength for 1, 2, and 28 days. In the mixtures, the air content was varied while cement factor and W/C were held constant so that slump could be varied for different mixtures and air content. The study shows that pulse velocity-strength relationship get affected for the air content. The study proposed that the slump should be corrected with proper adjustment of W/C. The velocity-strength relationship was observed for 2, 4, 6, 8.5, and 11.5% of air content. Pulse velocity and compressive strength at 28-day for 2% air content were $15.5x10^{-3}$ ft/sec and 41MPa respectively and 11.5% air content $13x10^{-3}$ ft/sec and 20MPa respectively. This sums up that as air content increases, both the compressive strength and pulse velocity decreases. Two different data sets for two mix proportions were also considered in order to compare between different mix proportions. 2-day and 28-day pulse velocity versus strength curves were plotted for 2% and 6% air content. It was observed clearly that, whether V_p-S is compared between 2-day and 2-day or 2-day and 28-day, the air content shows its effect similarly. In the end, the study proposed that in order to predict the strength of hardened concrete, it is necessary to adjust for air content in the process and it has to be considered as a variable for prediction equation.

1.3 Observation from the Literature Review

1. As much as compressive strength depends on the water content of concrete, UPV tends to follow the relation in similar fashion. Low water content not only increases compressive strength of concrete but also increases the velocity count due to more dense mass.

2. As concrete gains strength while aging, it also gives more velocity count relating velocity with compressive strength.

3. With high or low water content, change in development percentage of pulse velocity with respect to compressive strength is insignificant.

4. It becomes quite unclear and ambiguous if age and mixture proportion is considered for analysis simultaneously.

5. With constant paste content and varying coarse aggregate content in mixture proportion, pulse velocity remains almost same for any particular water content.

6. Presence of air entrapment decreases velocity count as it decreases compressive strength in a similar manner.

1.4 Objectives of the study

The objectives of the thesis can be enlisted as-

1. To determine compressive strength of concrete using ultrasonic pulse velocity.

2. To study the properties of concrete of relatively high water-cement ratio and different type of aggregates.

3. To study the establishment of structural health monitoring with UPV assessment.

1.5 Scope of the study

The scope of the study involves-

1. Experimenting the effect of variation in strength controlling parameters of concrete in compressive strength of concrete.

2. Studying the relative variation in pulse velocity of concrete with change in compressive strength.

3. Establishing standard velocity-strength relationship by relating compressive strength of concrete with pulse velocity.

4. Analyzing and comparing the compressive strength prediction with pulse velocity.

Chapter 2 Materials for Concrete

2.1 General

To carry out the experiment, different materials were used to gain distinct prospect on the study. These materials are chosen to have, not only a broad view on the overall scenario of the materials available in Bangladesh, but also to study their properties as a strength giving element for concrete mixture. Different codes of ASTM were followed regarding the tests of the materials in order find out their properties, mix designs, and compatibility.

Setting up a structural health monitoring system via non-destructive test such as ultra-sonic pulse velocity technique, needs to test for all types of commonly used material that are used in preparing concrete mixtures. It is because, for every types of materials used, their property for conductance of high frequency ultra-sonic pulse is different. In this thesis, a total of five types of coarse aggregates are used which are commonly available in Bangladesh. These aggregates are brick chips (BC), crushed stone (CS), black stone (BS), shingles (SG). Also, Iron Slag (IS) is tested along with other aggregates to find out its suitability for use as an aggregate. All of these aggregates are tested for their properties and later on for their strength giving ability with their high frequency conductance property.

In this chapter, properties of different materials that are used to make the concrete specimens are thoroughly described. Specific ASTM standards for carrying out different test methods are mentioned. The results from these tests are also described for different materials.

2.2 Binding Materials

As binding material, Portland composite cement (PCC) has been used. It has strength class of 42.5N; meaning, compressive strength of concrete at 28 days must exceed 30 N/mm^2 (i.e. higher than class C25/30 according to NBN B 15-001). These cements are also suitable for use at lower temperatures. In this thesis, CEM type-II/A-M is selected to carry out the experiments. This cement has about 80-94% of its contents as clinker and 6-20% of its contents as minerals. Specific gravity of cement was found out to be 2.9 by test carried according to ASTM specification C 188-14.

2.3 Coarse Aggregates

As the thesis is entitled, different types of aggregates available in Bangladesh are used in the experiment. These types are brick chips (BC), crushed stone (CS), black stone (BS), shingles (SG) and iron slag (IS). Each of these five aggregates was tested prior to use in preparing concrete mixture.

Table 2.1: Different Properties of Coarse Aggregates

Material Type	Fineness Modulus (FM)	% Wear	Bulk Specific Gravity (SSD)	Absorption (%)	Unit Weight (Kg/m^3)
Brick Chips (BC)	Is determined prior to casting according to ASTM C33	38.26	2.30	15.06	1023
Crushed Stone (CS)		38.76	2.56	0.46	2342
Shingles (SG)		27.3	2.58	1.24	1948

Material Type	Fineness Modulus (FM)	% Wear	Bulk Specific Gravity (SSD)	Absorption (%)	Unit Weight (Kg/m^3)
Black Stone (BS)	2.52	10.9	2.84	1.45	1836
Sylhet Sand		-	2.45	3.30	1550

2.3.1 Brick Chips

Bricks chips used in this experiment are crushed from bricks obtained from one of the local fields. The size was limited to 20 mm (3/4th down) maximum. The aggregates were washed and oven dried for all type of material testing.

The following table contains specific gravity of brick aggregates. Specific gravity in OD basis, SSD basis and apparent specific gravity along with %Absorption are determined. The tests are done according to ASTM C127.

The results are described and tabulated below

Table 2.2: Specific Gravity & % Absorption for Brick Chips

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (SSD)	Avg. Sp. Gr. (SSD)	Specific Gravity (Apparent)	Avg. Sp. Gr. (Apparent)
3000	3451	1930	2.3	2.3	2.8	2.8
3008	3449	1902	2.2		2.7	
3000	3445	1950	2.3		2.9	

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (OD)	Avg. Sp. Gr. (OD)	Absorption (%)	Avg. Absorption (%)
3000	3451	1930	2.0	2.0	15.0	14.8
3008	3449	1902	1.9		14.7	
3000	3445	1950	2.0		14.8	

Los Angeles abrasion tests are also performed to find out %wear value. ASTM C131 is followed in order to carry out the test. The results are described and tabulated as follows

Table 2.3: %Abrasion wear for Brick Chips

Mass of sample before test (g)	Mass retained on sieve size 1.70 mm (g)	Mass passing on sieve size 1.70 mm (g)	% wear	Avg. % wear
5009	3092.8	1916.2	38.3	38.3
5000	3086	1914	38.3	

2.3.2 Crushed Stone

The stone that are used as crushed stone are boulder crushed. The size was limited to 20 mm (3/4th down) maximum. The aggregates were washed and oven dried prior to all type of material testing.

The following table contains specific gravity of brick aggregates. Specific gravity in OD basis, SSD basis and apparent specific gravity along with %Absorption are determined. The tests are done according to ASTM C127.

Table 2.4: Specific Gravity & % Absorption for Crushed Stone

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (SSD)	Avg. Sp. Gr. (SSD)	Specific Gravity (Apparent)	Avg. Sp. Gr. (Apparent)
1600	1606	972	2.5	2.6	2.5	2.5
1700	1709	1004	2.4		2.4	
1700	1708	1080	2.7		2.7	

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (OD)	Avg. Sp. Gr. (OD)	Absorption	Avg. Absorption (%)
1600	1606	972	2.5	2.5	0.4	0.5
1700	1709	1004	2.4		0.5	
1700	1708	1080	2.7		0.5	

Los Angeles abrasion tests are also performed to find out %wear value. ASTM C131 is followed in order to carry out the test. The results are described and tabulated as follows

Table 2.5: %Abrasion wear for crushed stone

Mass of sample before test (g)	Mass retained on sieve size 1.70 mm (g)	Mass passing on sieve size 1.70 mm (g)	% wear	Avg. % wear
5000	3052	1948	39.0	38.8
5000	3072	1928	38.6	

2.3.3 Shingles

The shingles commonly known as "aluvutu" stone is used for thesis experiment. The size was limited to 20 mm (3/4th down) maximum. The aggregates were washed and oven dried prior to all type of material testing.

The following table contains specific gravity of brick aggregates. Specific gravity in OD basis, SSD basis and apparent specific gravity along with %Absorption are determined. The tests are done according to ASTM C127.

Table 2.6: Specific Gravity & % Absorption for Shingles

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (SSD)	Avg. Sp. Gr. (SSD)	Specific Gravity (Apparent)	Avg. Sp. Gr. (Apparent)
1000.8	1016.5	625	2.6	2.6	2.7	2.6
1004.9	1017	618.9	2.6		2.6	
1002	1011.4	620.9	2.6		2.6	

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (OD)	Avg. Sp. Gr. (OD)	Absorption	Avg. Absorption (%)
1000.8	1016.5	625	2.6	2.5	1.6	1.2
1004.9	1017	618.9	2.5		1.2	
1002	1011.4	620.9	2.6		0.9	

Los Angeles abrasion tests are also performed to find out %wear value. ASTM C131 is followed in order to carry out the test. The results are described and tabulated as follows

Table 2.7: %Abrasion wear for shingles

Mass of sample before test (g)	Mass retained on sieve size 1.70 mm (g)	Mass passing on sieve size 1.70 mm (g)	% wear	Avg. % wear
5000	3928	1072	21.4	21.4

2.3.4 Black Stone

Black Stones used in this experiment are commonly known as “hard stone”. The size was limited to 20 mm (3/4th down) maximum. The aggregates were washed and oven dried prior to all type of material testing.

The following table contains specific gravity of brick aggregates. Specific gravity in

OD basis, SSD basis and apparent specific gravity along with %Absorption are determined. The tests are done according to ASTM C127.

Table 2.8: Specific Gravity and % Absorption for Black Stone

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (SSD)	Avg. Sp. Gr. (SSD)	Specific Gravity (Apparent)	Avg. Sp. Gr. (Apparent)
2070	2100	1361	2.8	2.8	2.9	2.8
3000	3042	1902	2.7		2.7	

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (OD)	Avg. Sp. Gr. (OD)	Absorption	Avg. Absorption (%)
2070	2100	1361	2.8	2.7	1.4	1.4
3000	3042	1902	2.6		1.4	

Los Angeles abrasion tests are also performed to find out %wear value. ASTM C131 is followed in order to carry out the test. The results are described and tabulated as follows

Table 2.9: %Abrasion wear for Black Stone

Mass of sample before test (g)	Mass retained on sieve size 1.70 mm (g)	Mass passing on sieve size 1.70 mm (g)	% wear	Avg. % wear
5022	4473.2	548.8	10.9	11.0
5000	4450	550	11.0	

2.3.5 Iron Slag

Iron slag or steel slag is a common by product of steel re-rolling mills. In this thesis, one of the objectives is to find out the suitability of using Iron Slag as aggregates for construction purpose. Here, properties of Iron Slag are briefly discussed.

In steel re-rolling mills, for producing steel, sponge iron or pig iron and scrap iron are used. First they are collected, then they are put together in the furnace where melting of iron is done. Some smoke or flue dust are produced which are suctioned by large air vents to the other side of the mill where they are collected in bags. Upon heating and melting of the pig iron and scrap iron the liquid steel and slag are produced where they stay stratified. As the slag is less dense than melted steel, it floats over the liquid steel layer. After stratification is completed, the liquid steel is collected from the bottom and whenever the sloshing of slag occurs, separation is stopped immediately. To stabilize the product, often lime and silica are mixed. Lime and silica are both known to be the primary constituents of cement. So it can be suggested that, the processed slag also might have some cementitious property or hydration property.

Slag aggregates, upon being separated from liquid steel and processed, it is then crushed by hydraulic crusher. The crushed slags are then separated through magnetic means as they are being carried through a conveyor belt. The process is then repeated 3-4 times to ensure there are no slags remaining to recycle as a source of steel manufacturing. As they are cooled down to normal temperature, two methods are followed to bring the temperature down. One is to slow cooling by air circulation over the hot slags and another is the rapid cooling by sprinkling water over them. Slow cooling tends to form a hard and dense crystalline structure and rapid cooling results in formation of a brittle slag structure.

Steel slag, by its classification according to specific gravity and appearance, can be broadly categorized as three particular types, namely:

i. Light Weight Steel Slag (SL)
ii. Heavy Weight Steel Slag (SH)
iii. Mixed Steel Slag (SM)

In this study, steel slag is collected from a local manufacturing company. The objective is to find out their physical and chemical properties and also how do they respond to ultrasonic pulse velocity.

2.3.5.1 Light Weight Steel Slag (SL)

Iron Slag used in the tests are lighter and porous in nature. The size was limited to 20 mm (3/4th down) maximum. The aggregates were washed and oven dried prior to all type of material testing.

The following table contains specific gravity of brick aggregates. Specific gravity in OD basis, SSD basis and apparent specific gravity along with %Absorption are determined. The tests are done according to ASTM C127.

Table 2.10: Specific Gravity and % Absorption for Iron Slag (Light)

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (SSD)	Avg. Sp. Gr. (SSD)	Specific Gravity (Apparent)	Avg. Sp. Gr. (Apparent)
1483.3	1522.1	900	2.45	2.24	2.5	2.3
1336.3	1373.5	750	2.20		2.3	
1309.2	1345.3	700	2.01		2.1	

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (OD)	Avg. Sp. Gr. (OD)	Absorption	Avg. Absorption (%)
1483.3	1522.1	900	2.38	2.18	2.6	2.7
1336.3	1373.5	750	2.14		2.8	
1309.2	1345.3	700	2.03		2.8	

Los Angeles abrasion tests are also performed to find out %wear value. ASTM C131 is followed in order to carry out the test. The results are described and tabulated as follows

Table 2.11: %Abrasion wear for Iron Slag (Light)

Mass of sample before test (g)	Mass retained on sieve size 1.70 mm (g)	Mass passing on sieve size 1.70 mm (g)	% wear	Avg. % wear
5000.6	2706	2294.6	45.9	45.9

2.3.5.2 Heavy Weight Steel Slag (SH)

Iron Slag used in the tests are heavy with solid mass in nature. The size was limited to 20 mm (3/4th down) maximum. The aggregates were washed and oven dried prior to all type of material testing.

The following table contains specific gravity of brick aggregates. Specific gravity in OD basis, SSD basis and apparent specific gravity along with %Absorption are determined. The tests are done according to ASTM C127.

Table 2.12: Specific Gravity and % Absorption for Iron Slag (Heavy)

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (SSD)	Avg. Sp. Gr. (SSD)	Specific Gravity (Apparent)	Avg. Sp. Gr. (Apparent)
1000	1024	729.2	3.47		3.69	
1000	1017	732	3.57	3.57	3.73	3.72
1000	1017	731.8	3.57		3.73	

Mass of oven dry test sample in air, A	Mass of saturated surface dry test sample in air, B	Apparent mass of saturated test sample in water, C	Specific Gravity (OD)	Avg. Sp. Gr. (OD)	Absorption	Avg. Absorption (%)
1000	1024	729.2	3.69	3.47	2.4	1.93
1000	1017	732	3.51		1.7	
1000	1017	731.8	3.51		1.7	

Los Angeles abrasion tests are also performed to find out %wear value. ASTM C131 is followed in order to carry out the test. The results are described and tabulated as follows

Table 2.13: %Abrasion wear for Iron Slag (Heavy)

Mass of sample before test (g)	Mass retained on sieve size 1.70 mm (g)	Mass passing on sieve size 1.70 mm (g)	% wear	Avg. % wear
5000	4220	780	15.6	15.8
5000	4195	805	16.1	

2.3.5.3 Mixed Steel Slag (SM)

Iron Slag used in the tests are heavy with solid mass in nature. The size was limited to 20 mm (3/4th down) maximum. The aggregates were washed and oven dried prior to all type of material testing.

The following table contains specific gravity of brick aggregates. Specific gravity in OD basis, SSD basis and apparent specific gravity along with %Absorption are determined. The tests are done according to ASTM C127.

Table 2.14: Specific Gravity and % Absorption for Iron Slag (Mixed State)

Mass of oven dry test sample in air, A	**Mass of saturated surface dry test sample in air, B**	**Apparent mass of saturated test sample in water, C**	**Specific Gravity (SSD)**	**Avg. Sp. Gr. (SSD)**	**Specific Gravity (Apparent)**	**Avg. Sp. Gr. (Apparent)**
1000	1033	640	2.62	2.67	2.78	2.80
1000	1022	651	2.75		2.86	
1000	1022	637	2.65		2.75	

Mass of oven dry test sample in air, A	**Mass of saturated surface dry test sample in air, B**	**Apparent mass of saturated test sample in water, C**	**Specific Gravity (OD)**	**Avg. Sp. Gr. (OD)**	**Absorption**	**Avg. Absorption (%)**
1000	1033	640	2.54	2.61	3.3	2.57
1000	1022	651	2.70		2.2	
1000	1022	637	2.60		2.2	

Los Angeles abrasion tests are also performed to find out %wear value. ASTM C131 is followed in order to carry out the test. The results are described and tabulated as follows

Table 2.15: %Abrasion wear for Iron Slag (Mixed)

Mass of sample before test (g)	Mass retained on sieve size 1.70 mm (g)	Mass passing on sieve size 1.70 mm (g)	% wear	Avg. % wear
5000	3130	1870	37.1	37.4
5000	3115	188	37.7	

2.4 Gradation of Coarse Aggregate

Gradation of all the coarse aggregate in this thesis is guided by ASTM C33. From the gradation chart, 20mm (3/4th down) maximum size of aggregates, size-6 is chosen. Sizes are chosen in between 20mm to 9.5mm.

Table 2.16: Fineness Modulus of Coarse Aggregate

Sieve Size (mm)	% Retained	% Cumulative Retained	% Finer
25	0.00	0.00	100
20	5	5	95
12.5	65	70	30
9.5	30	100	0
4.75	0	100	0
2.36	0	100	0
1.18	0	100	0
0.6	0	100	0
0.3	0	100	0
0.15	0	100	0
Pan	-	-	
Total	100.00	675	
Fineness Modulus = 6.75			

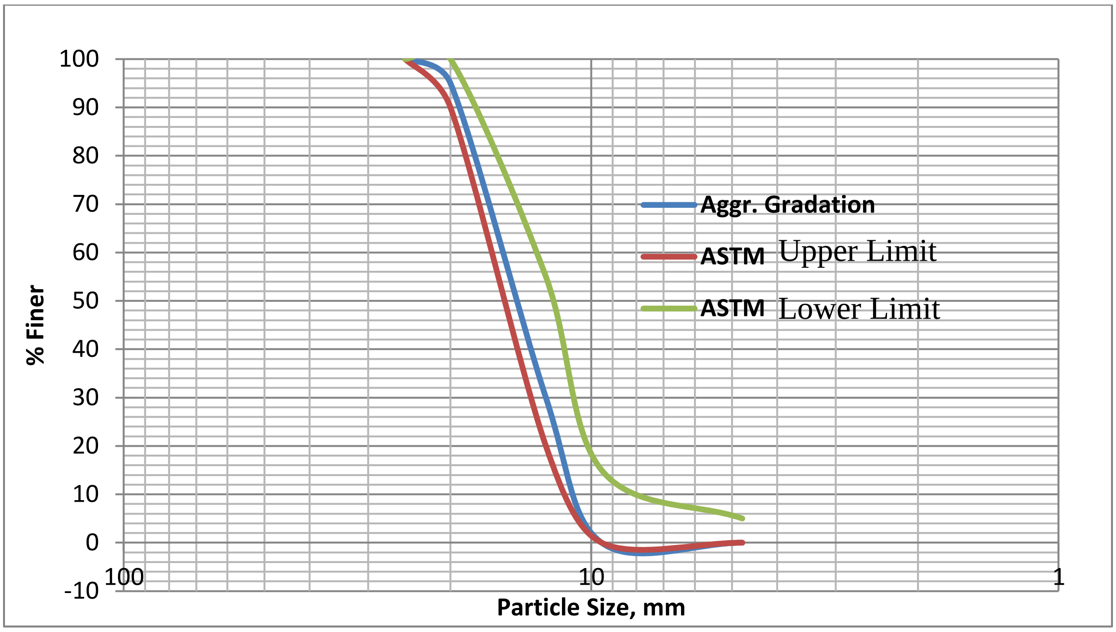


Figure: 2.1 Gradation Curve for Coarse Aggregate

2.5 Fine Aggregate

Fine aggregate used in this thesis is Sylhet sand. Sylhet sand is tested for specific gravity and %absorption value according to ASTM C128. Also sieve analysis of fine aggregate was performed according to C136.

Table 2.17: Specific Gravity and % Absorption of Sylhet Sand

Wt of pycnometer+ sample + water (g)	Wt. of pycnometer + water (g)	Wt. of SSD sample (g)	Wt. of OD sample (g)	Sp. Gr. (SSD)	Avg. Sp. Gr. (SSD)
1586.3	1274	516.5	500.0	2.4	2.5
1477.5	1227	414	401.2	2.5	

Apparent Sp. Gr.	Avg. Sp. Gr. (Apparent)	Absorption (%)	Avg. Absorption (%)
2.7	2.7	3.3	3.2
2.7		3.2	

Table 2.18: Fineness modulus of Sylhet sand

Type of Aggregate	Sieve Size (mm)	Retained Weight (g)	% Retained	% Cumulative Retained	% Finer
SS	50	0.00	0.00	0.00	100.00
	37.5	0.00	0.00	0.00	100.00
	20	0.00	0.00	0.00	100.00
	9.5	0.00	0.00	0.00	100.00
	4.75	2.00	0.40	0.40	99.60
	2.36	14.00	2.78	3.18	96.82
	1.18	95.00	18.89	22.07	77.93
	0.6	164.00	32.60	54.67	45.33
	0.3	109.00	21.67	76.34	23.66
	0.15	100.00	19.88	96.22	3.78
	Pan	19.00	3.78	100.00	0.00
	Total	503	100.00		
	FM = 2.5				

From the gradation of Sylhet sand we can find the graphical presentation of size distribution of sand as follows

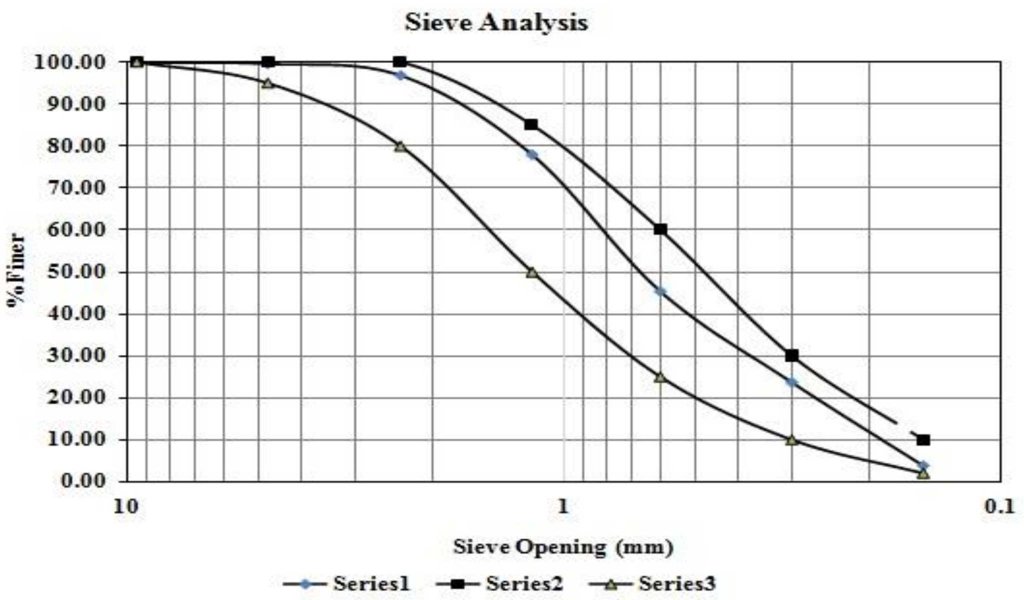


Figure: 2.2 Gradation Curve for Fine Aggregate

2.6 Conclusions

The material properties obtained are used later to address the reason behind various findings of the study. In this chapter, materials properties are addressed to quantify the nature and anticipate the likely behavior for different aggregates under many possible circumstances. The values not only a give a comprehensive understanding but also gives a brief idea about the suitability to many potential applications.

Chapter 3 Methodology

3.1 General

As the study has a wide insight on a variety of aspects, different methods were adopted in order to achieve the objective of this study properly. And by implementing these methods, a direct approach has been set out to fulfill the scope of the study. In this chapter, the methods adopted and implemented are discussed thoroughly. This involves the selection of key parameters for mixture proportions, the mix design, the testing parameters etc.

3.2 Cases Investigated

For proper insight of the study, different key parameters for mixture proportion are considered in the experiment. All of the cases that selected to carry out are performed with a weight based mix design approach. Although, keeping in mind the general practice in Bangladesh, some volume based mix ratios are also considered to relate to the actual field scenario.

3.2.1 Mixture Proportion

As the study involves different types of aggregate available in Bangladesh, the mix design is adopted in such a way that the comparative analysis of these aggregates are possible. With these aggregates, concrete is to be made and hence the main approach is to build a relationship between their compressive strength and ultrasonic pulse velocity (UPV).

3.2.1.1 Weight Based Mix Proportion

In weight based mix design approach; some considerations are made in order make the analysis with UPV more accurate. These considerations are-

a) Volumetric content (m3) of cement paste, fine and coarse aggregate should be constant.

b) Similar weight based content (Kg/m3) for cement and fine aggregate needs to be adopted for different types of aggregate.

c) Volumetric content (m3) of materials should be constant irrespective to their type.

And as for the key parameters of the weight based approach, following considerations are adopted in this study-

a) W/C – 0.45, 0.50, 0.55

b) s/a – 0.36, 0.44, 0.48

c) Cement – 395 Kg/m3, 372 Kg/m3, 351 Kg/m3

W = Water

C = Cement

s = Sand

s/a = Sand to total Aggregate Volumetric ratio

For the propagation of the ultrasonic pulse, it is very important to make sure that the interfaces through which the pulse will be pass, be constant in terms of cement paste and aggregate distribution. Although this cannot be completely brought under control, it is possible to make it as constant by approaching the volumetric content (m3) to be constant. This way, the constant paste content (%) and a constant volumetric content (m3) of fine and coarse aggregates, irrespective of the type can give a constant distribution of these materials.

By the order of availability in Bangladesh, the mix design tables for different types of aggregates are given below-

Table 3.1: Mix Design for concrete to be made with Brick chips aggregate

Mix Proportion Designation	W/C	s/a (%)	V_{Paste}, %	Mixture Proportion, Kg/m^3			
				Cement	Water	Fine Aggregate	Coarse Aggregate
BC-45-36-395	0.45	36	32	395	178	588	980
BC-50-36-372	0.50			372	186		
BC-55-36-351	0.55			351	193		
BC-45-40-395	0.45	40		395	178	652	919
BC-50-40-372	0.50			372	186		
BC-55-40-351	0.55			351	193		
BC-45-44-395	0.45	44		395	178	718	857
BC-50-44-372	0.50			372	186		
BC-55-44- 351	0.55			351	193		
The first two digits indicate W/C, the second two digits indicate sand to aggregate volume ratio in %, and the last three digits indicate cement content in kg/m^3.							

Table 3.2: Mix Design for concrete to be made with Crushed Stone aggregate

Mix Proportion Designation	W/C	s/a, %	V_{Paste}, %	Mixture Proportion, Kg/m^3			
				Cement	Water	Fine Aggregate	Coarse Aggregate
CS-45-36-395	0.45	36	32	395	178	588	1091
CS-50-36-372	0.50			372	186		
CS-55-36-351	0.55			351	193		
CS-45-40-395	0.45	40		395	178	652	1023
CS-50-40-372	0.50			372	186		
CS-55-40-351	0.55			351	193		
CS-45-44-395	0.45	44		395	178	718	955
CS-50-44-372	0.50			372	186		
CS-55-44-351	0.55			351	193		
The first two digits indicate W/C, the second two digits indicate sand to aggregate volume ratio in %, and the last three digits indicate cement content in kg/m^3.							

Table 3.3: Mix Design for concrete to be made with Shingles

Mix Proportion Designation	W/C	s/a, %	V_{Paste}, %	Mixture Proportion, Kg/m^3			
				Cement	Water	Fine Aggregate	Coarse Aggregate
SG-45-36-395	0.45	36	32	395	178	588	1100
SG-50-36-372	0.50			372	186		
SG-55-36-351	0.55			351	193		
SG-45-40-395	0.45	40		395	178	652	1031
SG-50-40-372	0.50			372	186		
SG-55-40-351	0.55			351	193		
SG-45-44-395	0.45	44		395	178	718	962
SG-50-44-372	0.50			372	186		
SG-55-44-351	0.55			351	193		
The first two digits indicate W/C, the second two digits indicate sand to aggregate volume ratio in %, and the last three digits indicate cement content in kg/m^3.							

Table 3.4: Mix Design for concrete to be made with <u>Black Stone</u>

<table>
<tr><th rowspan="2">Mix Proportion Designation</th><th rowspan="2">W/C</th><th rowspan="2">s/a, %</th><th rowspan="2">V_{Paste}, %</th><th colspan="4">Mixture Proportion, Kg/m^3</th></tr>
<tr><th>Cement</th><th>Water</th><th>Fine Aggregate</th><th>Coarse Aggregate</th></tr>
<tr><td>BS-45-36-395</td><td>0.45</td><td rowspan="2">36</td><td rowspan="6">32</td><td>395</td><td>178</td><td rowspan="2">588</td><td rowspan="2">1211</td></tr>
<tr><td>BS-50-36-372</td><td>0.50</td><td>372</td><td>186</td></tr>
<tr><td>BS-45-40-395</td><td>0.45</td><td rowspan="2">40</td><td>395</td><td>178</td><td rowspan="2">652</td><td rowspan="2">1135</td></tr>
<tr><td>BS-50-40-372</td><td>0.50</td><td>372</td><td>186</td></tr>
<tr><td>BS-45-44-395</td><td>0.45</td><td rowspan="2">44</td><td>395</td><td>178</td><td rowspan="2">718</td><td rowspan="2">1059</td></tr>
<tr><td>BS-50-44-372</td><td>0.50</td><td>372</td><td>186</td></tr>
<tr><td colspan="8">The first two digits indicate W/C, the second two digits indicate sand to aggregate volume ratio in %, and the last three digits indicate cement content in kg/m^3.</td></tr>
</table>

Table 3.5: Mix Design for concrete to be made with <u>Iron Slag</u>

<table>
<tr><th rowspan="2">Mix Proportion Designation</th><th rowspan="2">W/C</th><th rowspan="2">s/a (%)</th><th colspan="4">Mixture Proportion, kg/m^3</th></tr>
<tr><th>Cement</th><th>Water</th><th>Fine Aggregate</th><th>Coarse Aggregate</th></tr>
<tr><td>SL-45-36-395</td><td>0.45</td><td>36</td><td>395</td><td>178</td><td rowspan="3">588</td><td rowspan="3">955</td></tr>
<tr><td>SL-50-36-372</td><td>0.50</td><td>36</td><td>372</td><td>186</td></tr>
<tr><td>SL-55-36-351</td><td>0.55</td><td>36</td><td>351</td><td>193</td></tr>
<tr><td>SM-50-40-372</td><td rowspan="4">0.50</td><td>40</td><td>372</td><td>186</td><td rowspan="2">652</td><td>1066</td></tr>
<tr><td>SH-50-40-372</td><td>40</td><td>372</td><td>186</td><td>1414</td></tr>
<tr><td>SM-50-44-372</td><td>44</td><td>372</td><td>186</td><td rowspan="2">718</td><td>995</td></tr>
<tr><td>SH-50-44-372</td><td>44</td><td>372</td><td>186</td><td>1320</td></tr>
<tr><td colspan="7">The first two digits indicate W/C, the second two digits indicate sand to aggregate volume ratio in %, and the last three digits indicate cement content in kg/m^3.</td></tr>
</table>

3.2.1.2 Volume Based Mix Proportion

In order to relate the experimental work with field work, some cases are selected with volume based mix approach. Some very common key parameters for the mix design are considered such as-

a) Coarse aggregate : Fine Aggregate : cement = 1:1.5:3

b) Coarse aggregate : Fine Aggregate : cement = 1:2:4

c) W/C = 0.50

The volume base cases are only done for Iron slag (SM, SH). Hence it can be possible to compare the compressive strength of iron slag concrete with the commonly known brick aggregate concrete.

Table 3.6: Volume based mix proportions

Mix Proportion Designation	W/C	Mixture Proportion			
		Cement	Water	Fine Aggregate	Coarse Aggregate
SM-1:1.5:3	0.50	Volume based mixed design. Coarse Aggregate : Fine Aggregate : Cement = 1:1.5:3.			
SH-1:1.5:3	0.50	Volume based mixed design. Coarse Aggregate : Fine Aggregate : Cement = 1:1.5:3.			
SM-1:2:4	0.50	Volume based mixed design. Coarse Aggregate : Fine Aggregate : Cement = 1:2:4.			
SH-1:2:4	0.50	Volume based mixed design. Coarse Aggregate : Fine Aggregate : Cement = 1:2:4.			
Notations: SL – Lightweight slag, SH – Heavyweight slag, SM – Mixed slag					

3.2.2 Concrete Specimens

For testing purpose of this study, standard 100mmx200mm (4”x8”) size cylindrical shaped molds are used for making concrete specimens. Concrete specimens made with brick chips, crushed stone and shingles are casted accordingly to enable testing at 7, 28, 60 and 90 days. That means for each of the cases (3fc’+ (3fc’+2ft) + 3fc’+3fc’) 14 cylindrical specimens are casted. So, for brick chips, crushed stone and shingles (3x9x14) 378 specimens were casted. For Black stone six cases are considered for 28-day testing and the number of specimen for black stone is (6x5) 30. For iron slag, SL-45-36-395, SL-50-36-372, SL-55-36-351 cases are casted for 7, 28, 60 and 90- day testing giving (3x14) 42 specimens. And SM-50-40-372, SH-50-40-372, SM-50-44-372, SH-50-44-372 cases are casted for 28-day tests only which gives (4x5) 20 specimens. Some volumetric cases of iron slag, SM-1:1.5:3, SH-1:1.5:3, SM-1:2:4, SH-1:2:4 are also casted for 28-day test imparting (4x5) 20 specimens. Summing up all the cases, <u>we get total 44 cases with 490 cylindrical specimens.</u>

3.3 Casting of Specimens

3.3.1 Casting Procedure

For the casting of concrete of specimens, ASTM C31 is followed for standard procedure. Coarse aggregates and fine aggregates were brought upto surface saturated dry (SSD) condition before casting. All necessary precautions are taken as-

a) Prevention of drying of the bed on which casting is to be done.

b) Dampening of the sheet on which slump is to be taken is also prevented.

c) To prevent mortar attack and mixing, the sheets and wall of mixing machine are washed every time before a batch is mixed and casted.

d) Made sure that grease is applied to the wall of all cylindrical molds.

e) Made sure that proper distribution of paste and aggregate is done in casting all specimens.

f) The top surface of specimens must have a smooth surface, if that is not possible during casting, then capping with a thick mortar after half an hour of casting is provided.

g) It is mandatory to cast a specimen with a proper distribution of materials, such as, the top must get as much aggregate as the middle or bottom part of the specimen.

3.3.2 Slump

The concrete slump test is used for the measurement of a property of fresh concrete. The test is an empirical test that measures the workability of fresh concrete. More specifically, it measures consistency between batches. The slump cone has a base of 200mm (8”), a smaller opening at top of 100mm (4”) and a height of 300mm (12”). While performing the slump test, all three types of slumps are noticed. For collapse slump and true slump one reading is taken and for shear slump average reading is taken. To carry out the slump test, standard procedure is adopted from ASTM C143.

3.3.3 Curing

For the curing of specimens, a preliminary curing is done and followed by underwater curing. After casting, unmolding is to be done within 20±4 hours. Within this time range, the cylinder can often get dried and it is necessary to wrap its top surface with moist cloth to prevent that. It is done till unmolding and called preliminary curing. After unmolding, specimens are brought underwater and cured till performing the crushing tests.

3.4 Testing of Specimens

3.4.1 Measuring of Ultrasonic Pulse Velocity (UPV)

For measuring the ultrasonic pulse velocity, a pulse velocity instrument is needed. It has a transducer and receiver. The transducer generates pulse where the receiver receives the pulse. A coupling media (gel) is applied to the ends of a cylindrical specimen in order to provide a proper condition for transducing and receiving. The frequency of the pulse is kept at 54 kHz. The transducer and receiver are held at both ends of the specimens. The pulse is generated and time elapsed between pulse generation and receiving at the other end is recorded. By dividing the length of cylinder to the time we get the pulse velocity. The standards are adopted from ASTM C597 to carry out the test.

3.4.2 Compressive Strength

Compressive strength tests are performed as the cases are planned to investigate at 7, 28, 60 and 90-days. Crushing test is done in the semi-auto crushing machine. As per the procedure of the test, ASTM C39 standard is followed. Following precautions are adopted-

a) The top surface must be smooth, if not, capping is provided.

b) A base plate and top plate is applied to ensure uniform load distribution.

c) Load rate adopted from the standard (0.023MPa/s) is to be maintained throughout the crushing.

d) After each test the base plate of the machine is to be wiped for crushed particles.

3.4.3 Tensile Strength

Tensile strength tests are performed at 28-day. Tests are performed in universal testing machine (UTM). For the test, split tensile approach is adopted. As per the procedure of the test, ASTM C496 standard is followed. Following precautions are adopted-

a) The side of the cylindrical specimen needs to be smooth.

b) The specimens need to be placed in the center position of base plate carefully.

c) Load rate adopted from the standard is to be maintained throughout the test.

d) After each test the base plate of the machine is to be wiped for crushed particles.

3.4.4 Young's Modulus

In order to find out the young modulus of concrete specimens, an extensometer is applied to all the specimens during performing crushing test. The extensometer has two identical dial gauges. Readings are taken from the two gauges and average values are used to find the stress-strain plot and young's modulus. Readings from the extensometer are taken in every 5KN interval of crushing load applied. The dial gauge readings are averaged and multiplied by 0.01 to get deformation value in mm. From there strain value is calculated for each of the loads applied. Young's modulus is calculated at a strain of 0.0005 by dividing the corresponding stress to 0.0005. Young's modulus is calculated in Psi. Following precautions are adopted-

a) The extensometer needs to be properly set on the specimen, the spikes needs to be gripped tightly to the specimen.

b) All the fastening bolts need to be loosened to make sure that the spikes holding the specimen is not jammed, because otherwise gauge will not give deformation.

c) The dial gauges needs to be calibrated to zero before each test.

d) While handling the specimen from one place to another, the specimen should not be held gripping on the extensometer, because this way the spikes may slip.

e) While calculating strain, the length is to be considered is the distance between upper and lower spikes.

3.5 Conclusion

In this chapter, different methods adopted to achieve the objectives of the study are thoroughly discussed. Different testing parameters are explained in order to relate it to the study result. Experimental method is important in order to set out the scope the study. So, the methodology is followed by result and discussion in the next chapter.

Chapter 4 Results and Discussion

4.1 General

In order to establish the relationship between ultrasonic pulse velocity (UPV) and compressive strength of concrete, different cases are investigated in this study. Different commonly available aggregates are tested for establishing the relationship so that structural health monitoring system can be introduced. Although extensive investigations on different strength regarding parameters are needed, in this study a preliminary approach is taken to relate UPV with different strength regarding parameters. By relating to these parameters, it is possible to investigate thoroughly the nature and behavior of UPV in concrete, to know exactly what can be achieved adopting this non-destructive technique and its shortcomings.

As from the previous chapter of *Methodology*, the study has fixed some definite key parameters to run a thorough investigation. Different s/a ratios, W/C ratios, cement content variations and all constant volumetric content (m^3) for materials irrespective of their types are considered to have a broad insight into the study. So, in order to state the results and findings of the study and to discuss them, it is necessary to fix some key parameters.

In this chapter, the results of the study conducted will be quantified. It will be discussed elaborately in order to establish the relationship and analyze different aspects of UPV. Variations in slump values, effect for water content variations, effect for cement content variations, effect for different s/a ratios, effect of curing period, comparative tensile strength and young's modulus, effect on static elastic modulus, dynamic elastic modulus and shear modulus of rigidity etc. is discussed in this chapter. Finally, some relationships are proposed regarding the different mixing parameters and type of materials being used.

These relationships can be used to measure the strength of concrete up to a certain degree of accuracy. Different aspects of these relationships will be discussed and also the degree of accuracy will also be determined and discussed at the end of this chapter.

4.2 Simplified Approach

In order to establish relationship between ultrasonic pulse velocity and compressive strength of concrete, a general relationship has been approached by relating the strength directly to the UPV. Some commercial tests have been conducted in IUT concrete lab, form where some data are acquired and plotted. From the following plots of strength Vs. UPV (Fig. 4-1, 4-2, 4-3, 4-4), it can be observed that strength of concrete be likely to have an increasing trend with the UPV of concrete. But, whether it has linear trend is questionable. It is because of the fact that the plot is not only very ambiguous but also it has not been related to any strength regarding parameters like W/C ratio or s/a ratio. Very less value of coefficient of determination (the square of the Pearson product moment correlation coefficient, R^2=0.5853, 0.1094, 0.8879, 0.5565) also indicates that the linear trend found in the plots might not be the actual relationship between compressive strength and UPV of concrete.

The conclusion established from this simplified approach states that the increasing UPV of concrete indicates its increased strength. Whether it is an M15 or M20 grade concrete or whether it is 100mmx200mm or 150mmx300mm cylindrical specimens or 150mmx150mmx150mm cube specimens for that matter.

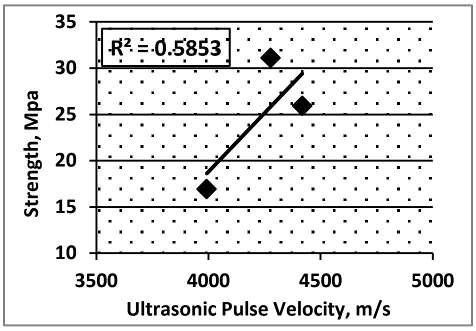


Figure: 4-1 **(1:2:4, 100mmx200mm)**

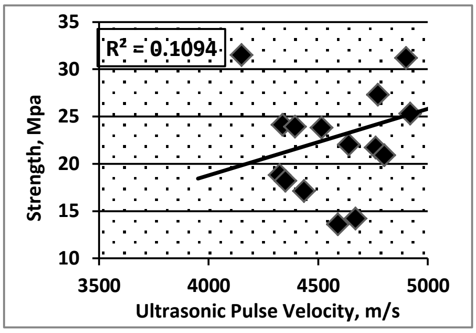


Figure: 4-2 **(1:1.5:3, 100mmx200mm)**

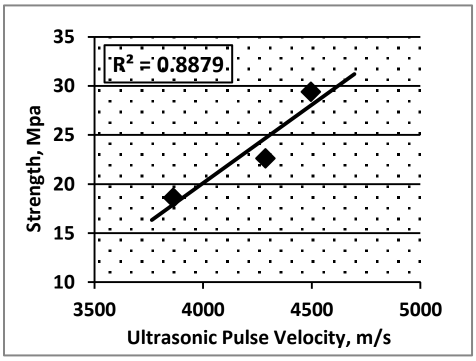


Figure: 4-3 **(150mmx300mm Specimen)**

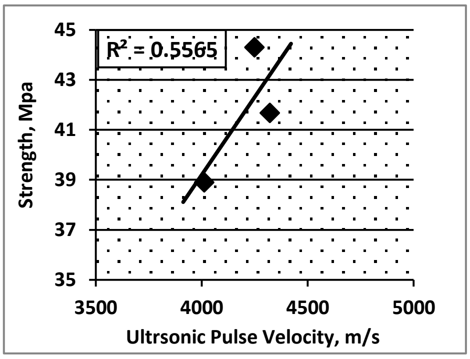


Figure: 4-4 **(150mmx150mm Specimen)**

4.3 Workability

It is customary to know how much workable the concrete will be prior to casting. As many times it presents a problem during casting in congested areas like beam-column joints, a preliminary idea is necessary about the workability of concrete. W/C plays a very important role in this regard but the aggregates used for the concrete also have a significant effect.

The following figure **(Fig. 4-5)** shows an overall comparison of all the aggregates used in this study. For similar cases we see their variations. It can be observed that, concrete made with brick aggregate has the lowest workability where other aggregates exhibit high workability profile. Concrete made with shingles have better workability compared to concrete made with crushed stone. Although concrete made with crushed stone has somewhat similar workability with similar concrete made with black stone. However, concrete made with iron slag seems to have unexpected increasing slump value imparting high workability.

Firstly, it can be clearly observed that, with increasing sand to aggregate volume ratio the workability of concrete tends to increase. Concrete made with brick chips has the lowest workability among all because of its high water absorption rate than the other aggregates. Iron slag has higher workability as it has low water absorption rate. Concrete made with crushed stone shows less workability than shingles as it has less void inside.

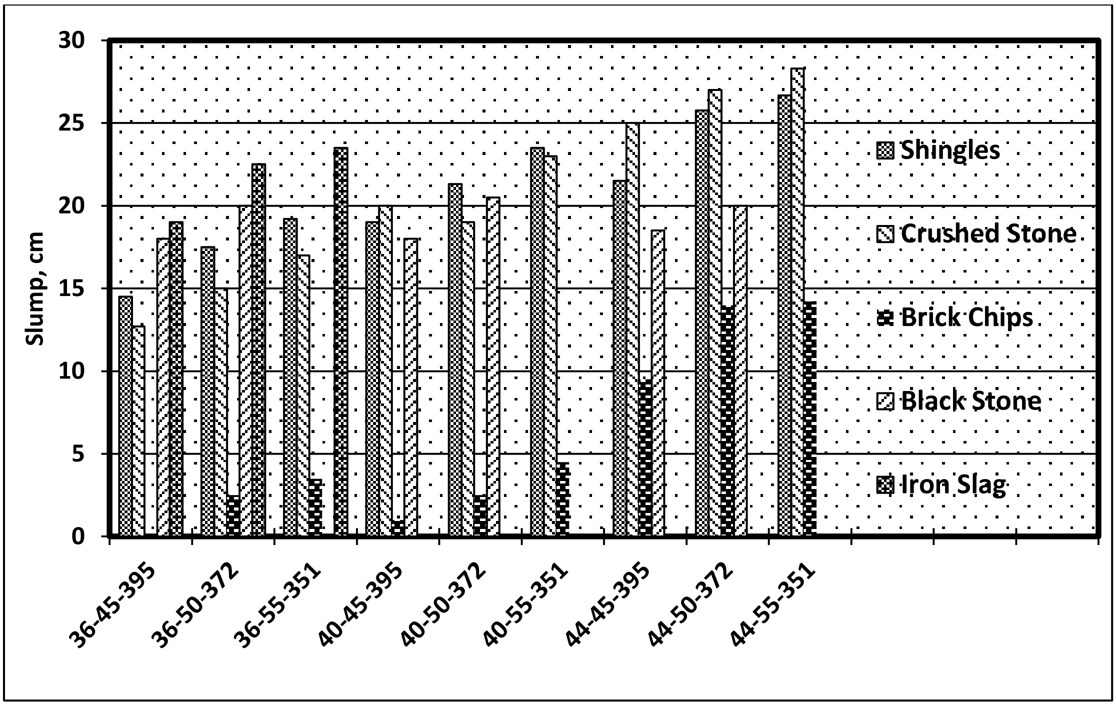


Figure: 4-5 **Workability of concrete**

4.4 Unit Weight

The unit weight of concrete for different types of aggregate are shown in the following figures (Fig. 4-6, 4-7, 4-8, 4-9). Unit weight variations in terms of curing period can also be observed from the plots. Variations in unit weights are mainly because of greater specific gravity of one aggregate than the others. Highest variation in unit weight of similar concrete for aggregate to aggregate variation is observed in 28 days when the concrete ted to achieve almost 80%-85% of its strength indicating most of the hydration is done within this time (28 days).

Unit weight variation for 7 days, 60 days or 90 days are not visible that much because of less hydration being occurred. Although, Iron slag has an unexpectedly increasing unit weight observed, the reasons to which needs further investigation to find out.

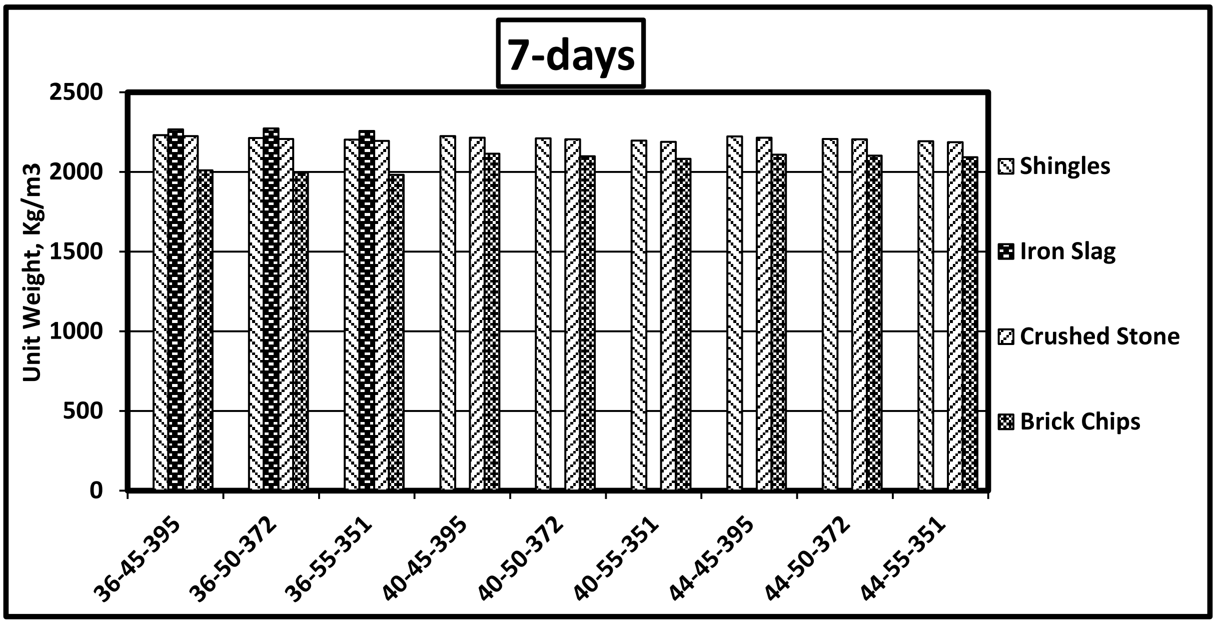


Figure: 4-6 **Unit Weight of concrete (7 Days)**

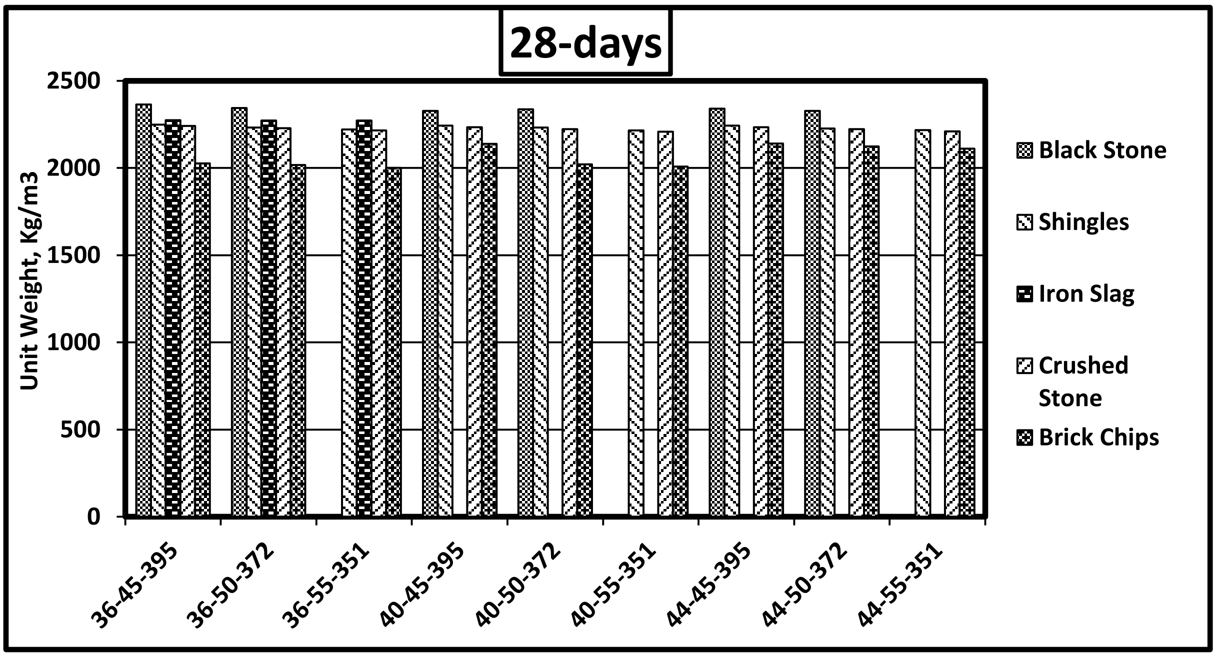


Figure: 4-7 **Unit Weight of concrete (28 Days)**

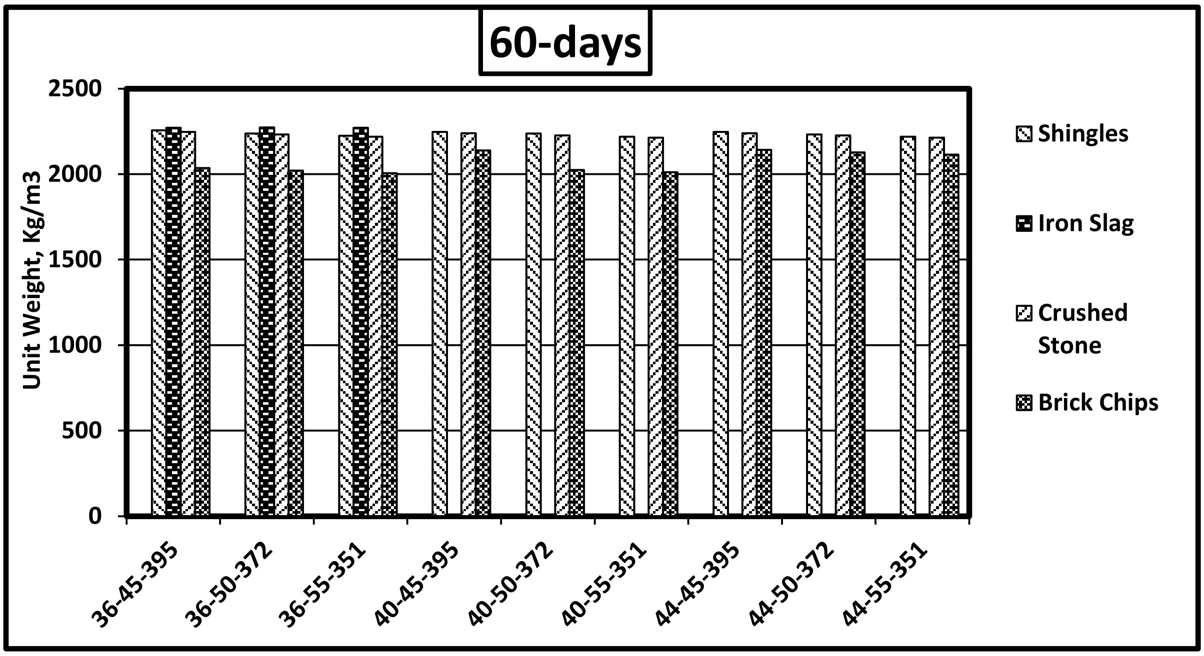


Figure: 4-8 **Unit Weight of concrete (60 Days)**

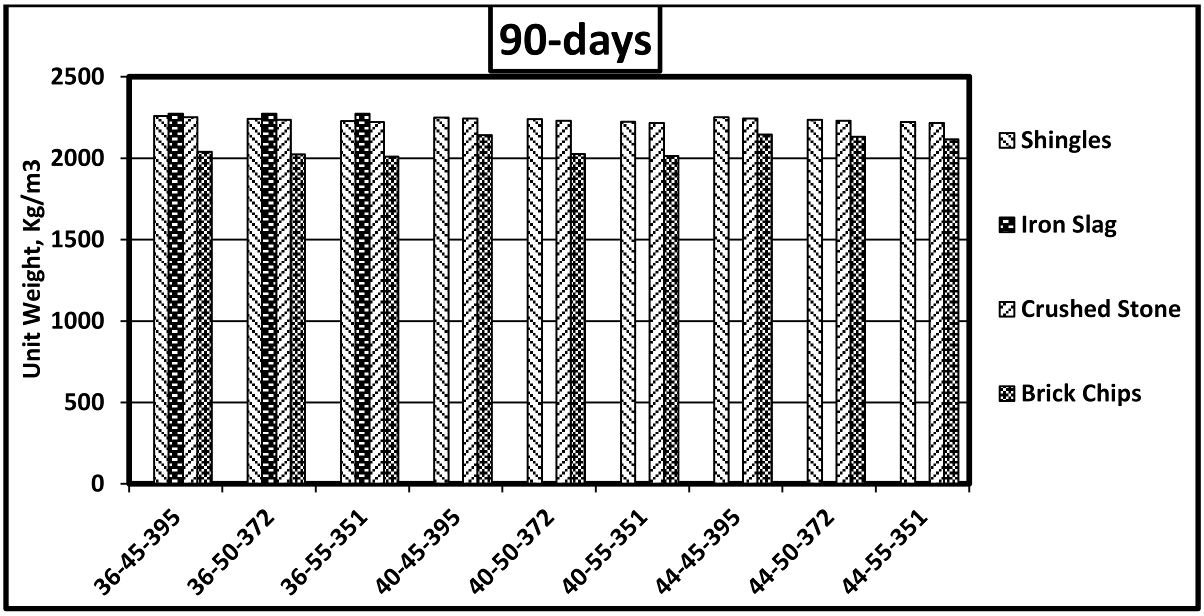


Figure: 4-9 **Unit Weight of concrete (90 Days)**

4.5 Sand to aggregate volume ratio (s/a)

In this sub clause, compressive strength of concrete and ultrasonic pulse response behavior of concrete in terms of pulse velocity will be discussed thoroughly. It is known that with change in sand to aggregate ratio (s/a) the compressive strength of concrete changes accordingly. In this study, it is also observed how that UPV changes with the variation in s/a ratio. Compressive strength is being related with UPV and a suitable trend is found.

First, an ideal scenario of concrete made with crushed stone aggregate is discussed here thoroughly. Then the other cases are presented with their respective plots. In crushed stone aggregate first if we consider the s/a ratio of 0.36, 0.40 and 0.44 for 7 Days, we can clear find a trend in strength Vs. UPV of concrete which is a *negative exponential regression*. The found plot has a high Pearson Correlation Coefficient, R^2 indicating that the regression is a best fit.

Now, by observing the plots it is clear that with decreasing W/C ratio the strength tends to increase and the UPV for concrete tends to increase too. But with increasing s/a ratio, the strength tends to increase although the UPV of concrete tends to decrease.

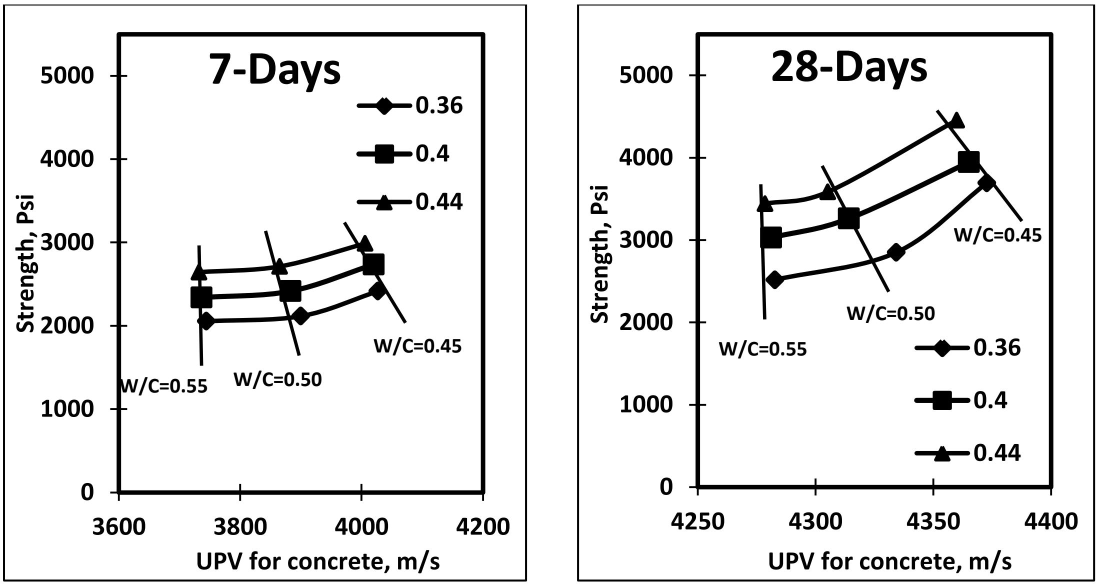


Figure: 4-10 **Strength vs. UPV for Crushed Stone (7, 28 Days)**

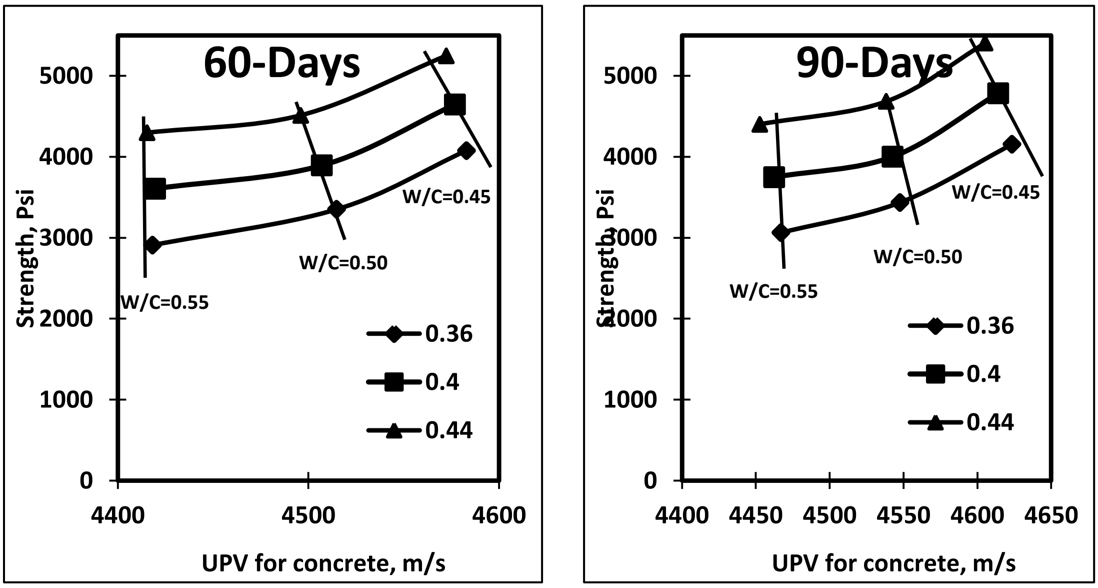


Figure: 4-11 **Strength vs. UPV for Crushed Stone (60, 90 Days)**

The reason for this is due to compaction of concrete. Although it is common that decrease in the strength occur with increase in s/a ratio. But in this study as the mix design is prepared in such a way that even if the s/a ratio changes only V_{CA} and V_{FA}

changes as other parameters are fixed. This results in compaction and thus the surface at which load is applied becomes stronger. So the compressive strength is being increased with increasing s/a ratio. But for similar scenario, the UPV tends to decrease as CA content is decreasing.

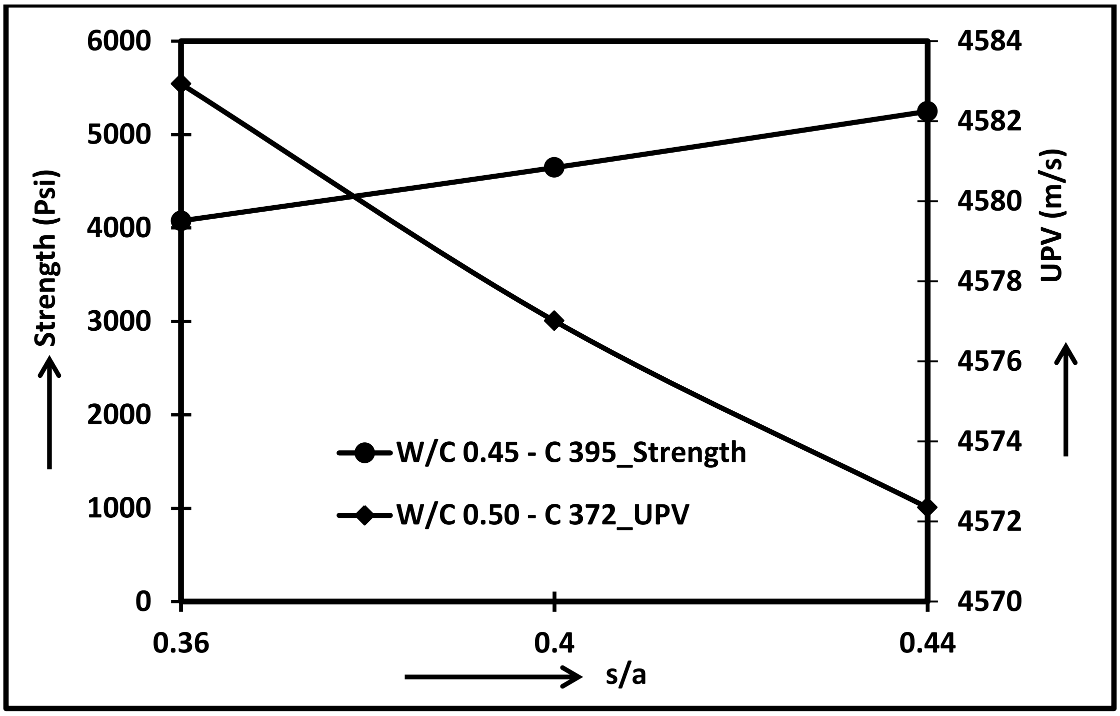


Figure: 4-12 **Strength & UPV variation for different s/a**

For concrete made with other aggregates are observed to follow similar trends. Their Strength and UPV for concrete vary similarly with different s/a ratio.

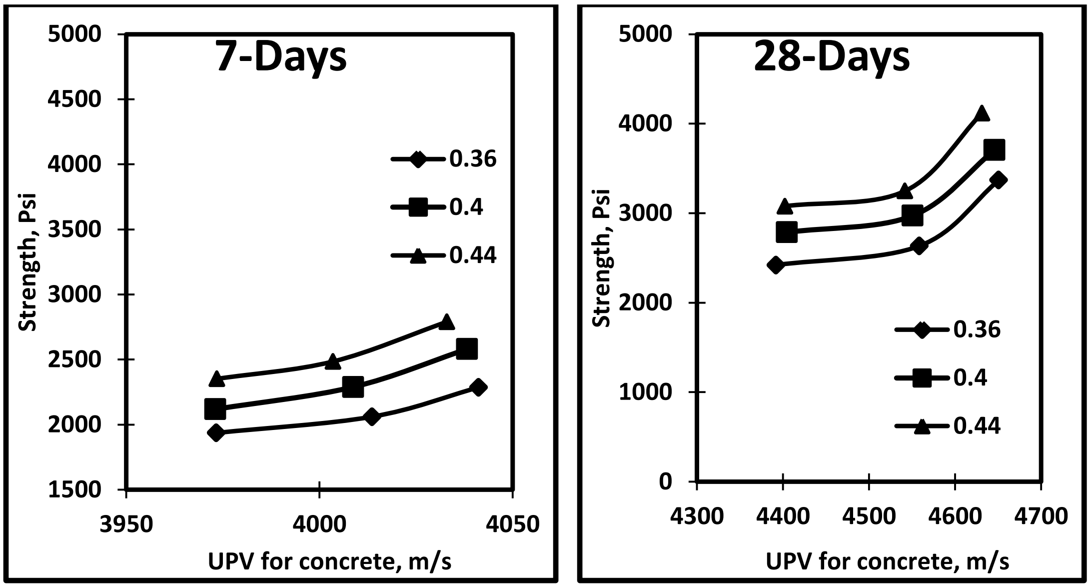


Figure: 4-13 **Strength vs. UPV for Shingles (7, 28 Days)**

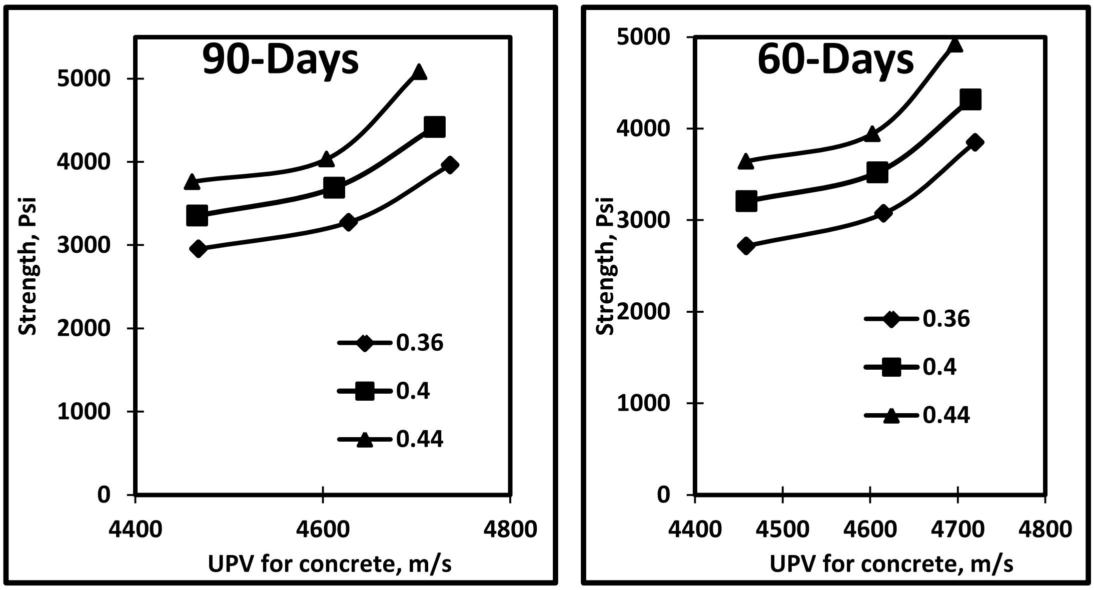


Figure: 4-14 **Strength vs. UPV for Shingles (60, 90 Days)**

From the above plots of shingles, it can be observed that the strength of concrete made by shingles is inferior to concrete made by crushed stone. There are several reasons for this kind of behavior. One of fact that can be attributed behind this is crushed stone is angular in shape and shingles is rounded. So there will be much more interlocking between the aggregates when concrete is made with it where concrete made with shingles will not have as much compactness due to less interlocking of aggregate, thus having voids inside concrete imparting less strength. Also, due to good interlocking of aggregate, less bleeding occurs in concrete made with crushed stone as water cannot move upward. But in case of shingles, due to voids inside, water comes up to the top surface more easily thus occurring more bleeding. The surface of shingles is much older than crushed stone aggregate, as the crushed stone comes from crushing of boulders imparting new surfaces. Older surface of shingles might not be stronger than crushed stone. Although good bonding between crushed stone aggregate inside the concrete makes the surface, upon which load will be applied, more rigid and stronger than that of shingles exhibiting better strength.

Another observation can be made from the plots of shingles and crushed stone is that, although concrete made with crushed stone has superior strength over similar concrete made with shingles, the UPV for concrete found out to be better in concrete made with shingles. Recall that the %abrasion value for shingles (21.4%) was found out to be better than that of crushed stone (38.8%) in the chapter *Materials for Concrete*. This indicates that although the surface of crushed stone is newer than the shingles, resistance over impact load is better for shingles meaning shingles used in this study is harder in mass than crushed stone, which helped the pulse getting passed within shorter period of time.

From the following plots of brick, black stone and iron slag, we can compare their strength and UPV for Concrete. It can be observed from the following plots that concrete aggregate made with brick chips has much lower strength at 28-days than the other conventional aggregate build concrete. This is because of the high abrasion percentage of the aggregate which indicates its vulnerability under heavy loading. Also the specific gravity which is only 2.30 indicates a much less dense aggregate and lower unit weight value like 1023 kg/m^3 confirms the comparatively less dense mass concrete than the concrete made with stone aggregates.

Comparatively, the concrete made with black stone has relatively very high strength. Amongst all the weight based case, the highest strength is observed at 28-days. Very less percentage abrasion value (10.9%) indicates its high sustainability and resistance under heavy loading. Its high specific gravity (2.84) and highest unit weight among the other aggregates (1836) are responsible for its superior strength over other concrete specimens.

As for the concrete made with iron slag aggregate, light weight (SL), mixed (SM) and heavy (SH) slags are used for making concrete specimens. Concrete made with light weight slag seems to have significantly low strength than the specimens built with other aggregates. This is because of the light weight slag being very fragile as aggregate. Having the highest percentage abrasion value (45.9%) among the other aggregates, it is very much susceptible to loading condition. Its specific gravity is also the lowest (2.24) indicating the aggregate having a less dense mass and absorption rate is quiet high (2.7%) compared to others indicating light weight slag might not be suitable for heavy loading conditions.

Although concrete made with mixed and heavy weight slag imparts a better strength than the light weight slag aggregate. Somewhat parallel strength is observed for similar concrete made with brick aggregate and mixed slag (SM). Concrete made with heavy weight slag (SH) however, gives better strength than specimens prepared with mixed slag and more likely comparable with similar concrete made with shingles. Some volumetric cases were also tested for 28 days with M15 and M20 grade concrete. They gave much better strength than weight based cases and the concrete made with heavy weight slag (SH) with M20 grade mixing proportion provided strength as much as 5041.14Psi.

The variation in UPV for concrete is dependent on some factors such as, how dense and hard mass the concrete is, how strong or dense the aggregate is, the principle constituents of the aggregates etc. From the plots it can be observed that concrete made with black stone has the highest recorded UPV. It can be easily understood form the black stone material property as it as a very dense and strong aggregate. Second highest UPV is recorded for concrete made with shingles, which gave less strength than similar concrete made with crushed stone. The fact that the surface of the shingles being older than crushed stone aggregate, its resistance to impact loading is better as it is being indicated by their percentage abrasion values (SG=27.3% < CS=38.76%). It shows the shingles is stronger in texture than crushed stone, so the UPV for concrete made with shingles is higher.

Next to crushed stone, concrete made with iron slag have higher UPV for concrete than that of brick aggregate. Although the brick is stronger and denser than light weight aggregate and the concrete made with brick aggregates shows better strength too, it is the principle constituents of iron slag that is responsible for high UPV. Iron slag has high iron content in it, making the ultrasonic pulse travel faster than anticipated. UPV for concrete made with heavy weight slag (SH) is recorded with UPV comparable to UPV for concrete made with crushed stones.

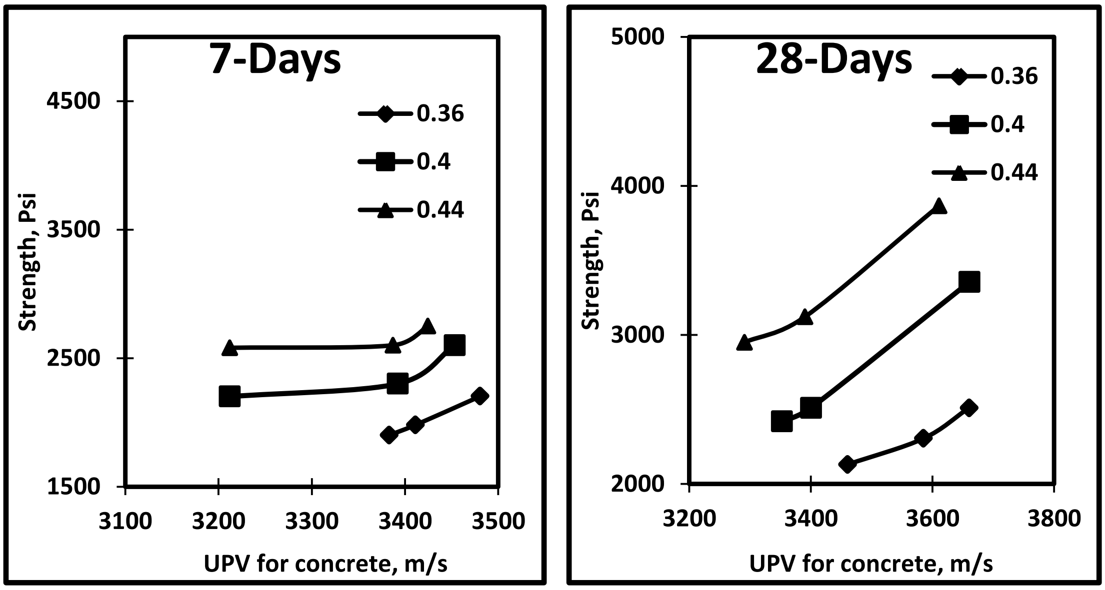


Figure: 4-15 **Strength vs. UPV for Brick Chips (7, 28 Days)**

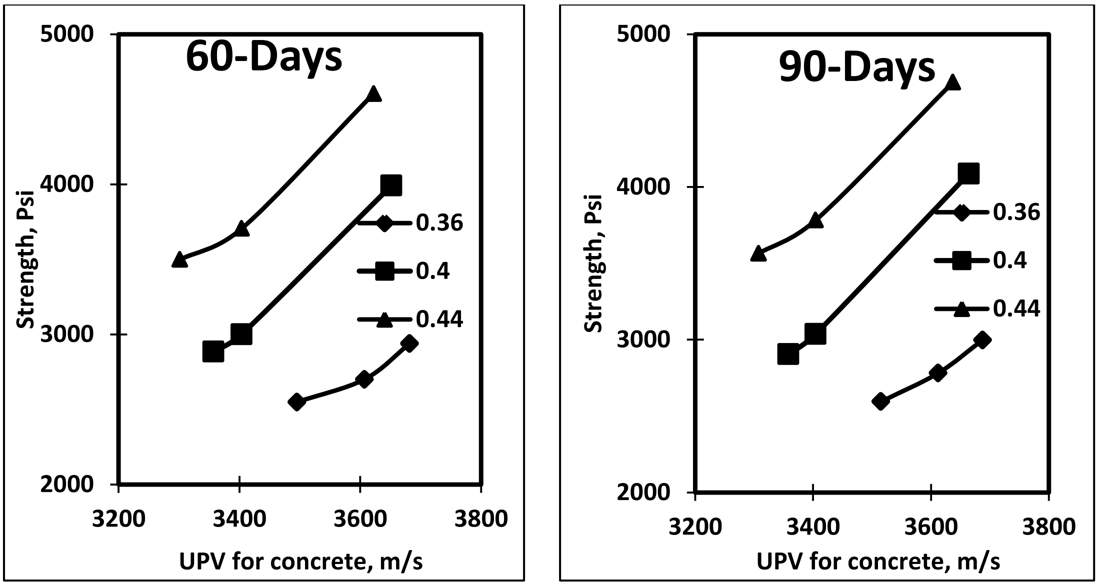


Figure: 4-16 **Strength vs. UPV for Brick Chips (60, 90 Days)**

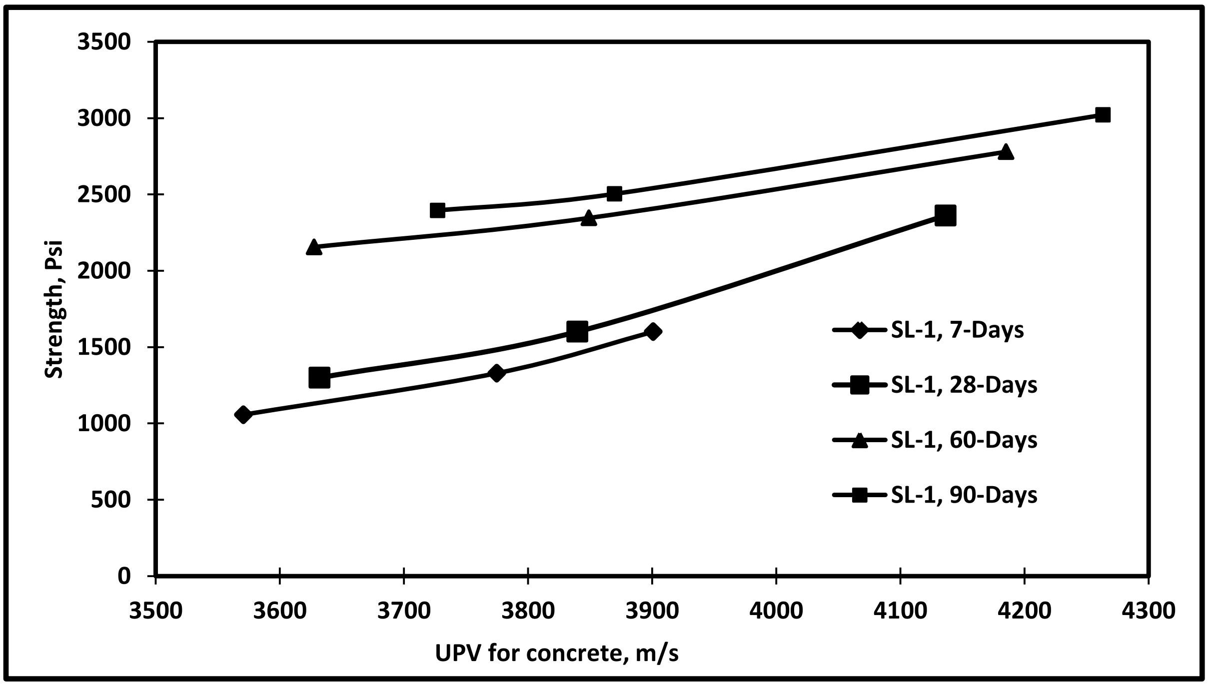


Figure: 4-17 **Strength & UPV for concrete made with Iron Slag (Light)**

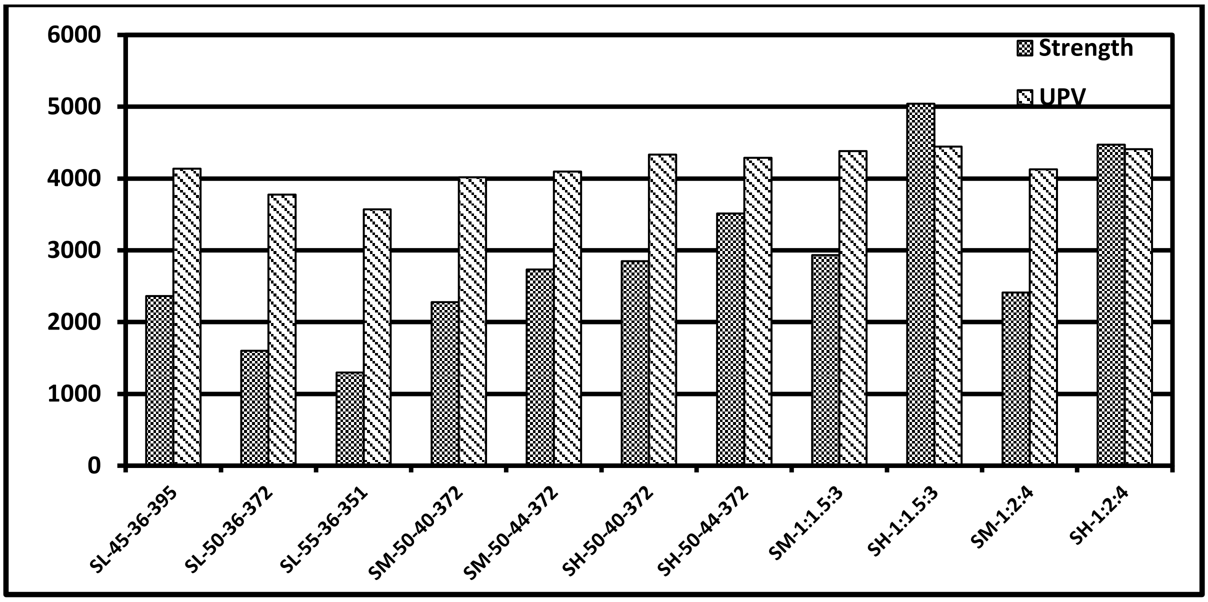


Figure: 4-18 **Strength & UPV for concrete made with Iron Slag (SL, SM, SH)**

Table 4-1: Regression equations obtained for different aggregates (28-Days)

s/a Ratios	Crushed Stone	Shingles	Brick	Iron Slag
0.36	$f'_c = 0.00004e^{0.0042V_p}$	$f'_c = 13.01e^{0.0012Vp}$	$f'_c = 131.94e^{0.0008Vp}$	$f'_c = 29.561e^{0.0011Vp}$
0.40	$f'c = 0.0034e^{0.0032Vp}$	$f'c = 19.545e^{0.0011Vp}$	$f'c = 65.083e^{0.0011Vp}$	-----
0.44	$f'c = 0.0025e^{0.0033Vp}$	$f'c = 15.619e^{0.0012Vp}$	$f'c = 168.93e^{0.0009Vp}$	----

Table 4-2: Regression equations obtained for different aggregates (60-Days)

Cases	Crushed Stone	Shingles	Brick	Iron Slag
0.36	f'c = $0.397e^{0.002Vp}$	f'c = $8.4591e^{0.0013Vp}$	f'c = $188.81e^{0.0007Vp}$	f'c = $403.82e^{0.0005Vp}$
0.40	f'c = $3.2767e^{0.0016Vp}$	f'c = $20.402e^{0.0011Vp}$	f'c = $67.519e^{0.0011Vp}$	-----
0.44	f'c = $15.672e^{0.0013Vp}$	f'c = $16.77e^{0.0012Vp}$	f'c = $190.28e^{0.0009Vp}$	----

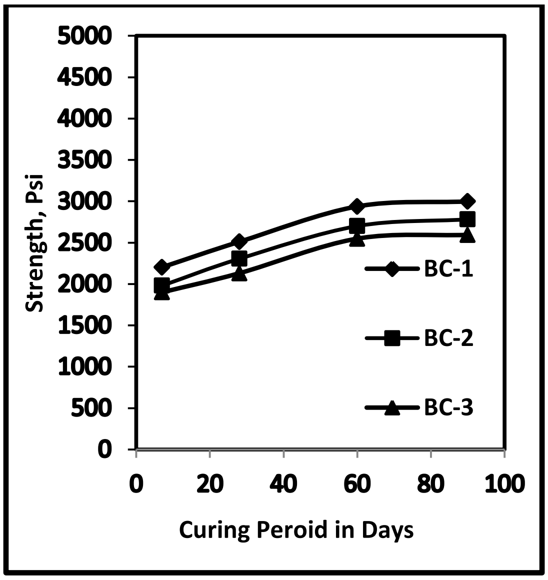
Table 4-3: Regression equations obtained for different aggregates (90-Days)

Cases	Crushed Stone	Shingles	Brick	Iron Slag
0.36	f'c = $0.5101e^{0.0019Vp}$	f'c = $25.403e^{0.0011Vp}$	f'c = $137.97e^{0.0008Vp}$	f'c = $456.03e^{0.0004Vp}$
0.40	f'c = $3.0115e^{0.0016Vp}$	f'c = $28.726e^{0.0011Vp}$	f'c = $66.295e^{0.0011Vp}$	-----
0.44	f'c = $12.312e^{0.0013Vp}$	f'c = $18.061e^{0.0012Vp}$	f'c = $215.96e^{0.0008Vp}$	----

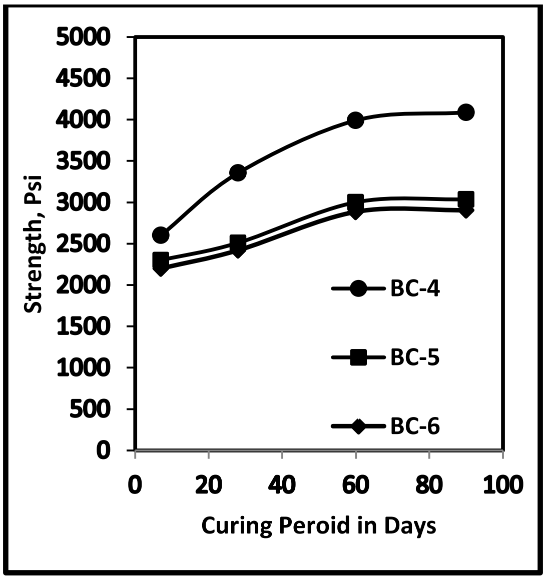
4.6 Age

The trend concrete tends to follow regarding both compressive strength and UPV will be discussed here elaborately. Although concrete tends to follow usual trend as per our findings, the variation of ultrasonic pulse velocity (UPV) with age of concrete specimens is different in some aspects. In order to fully understand the behavior of UPV with age it is analyzed considering different possible aspects.

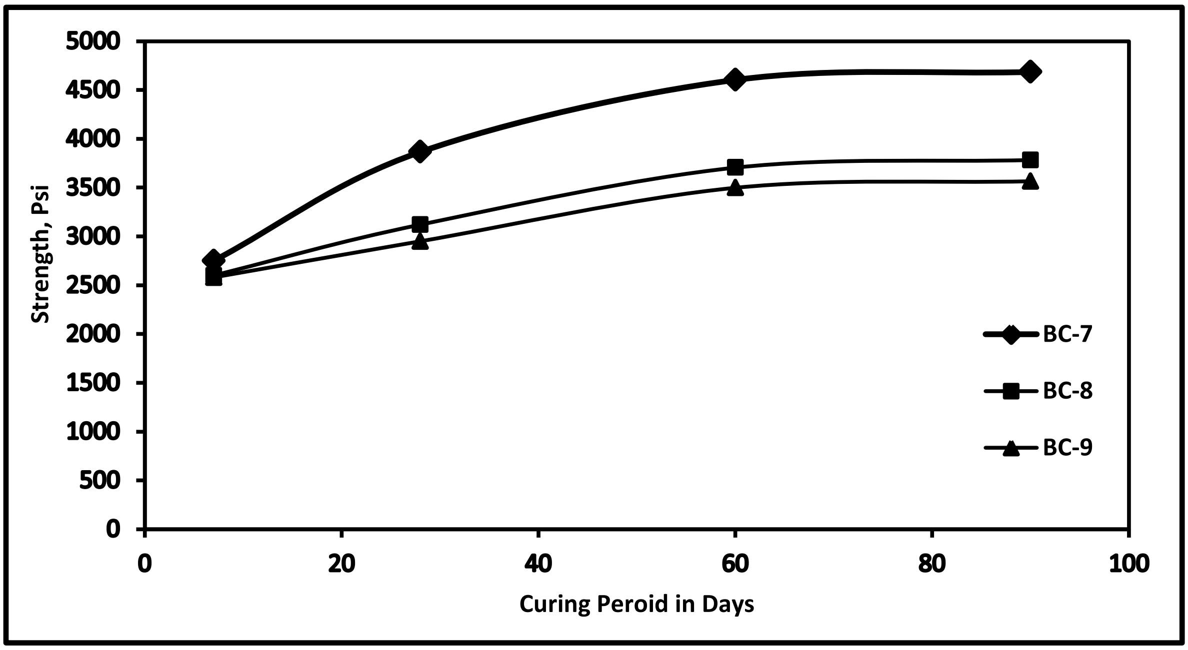
In our study, for all the different types of aggregate, the relationship between compressive strength of concrete and age of specimens is found out as a usual relationship. Tests are performed at 7, 28, 60 and 90-days. Also %developments of compressive strength against age are plotted too by considering 90-day strength as ultimate strength of concrete



(a)



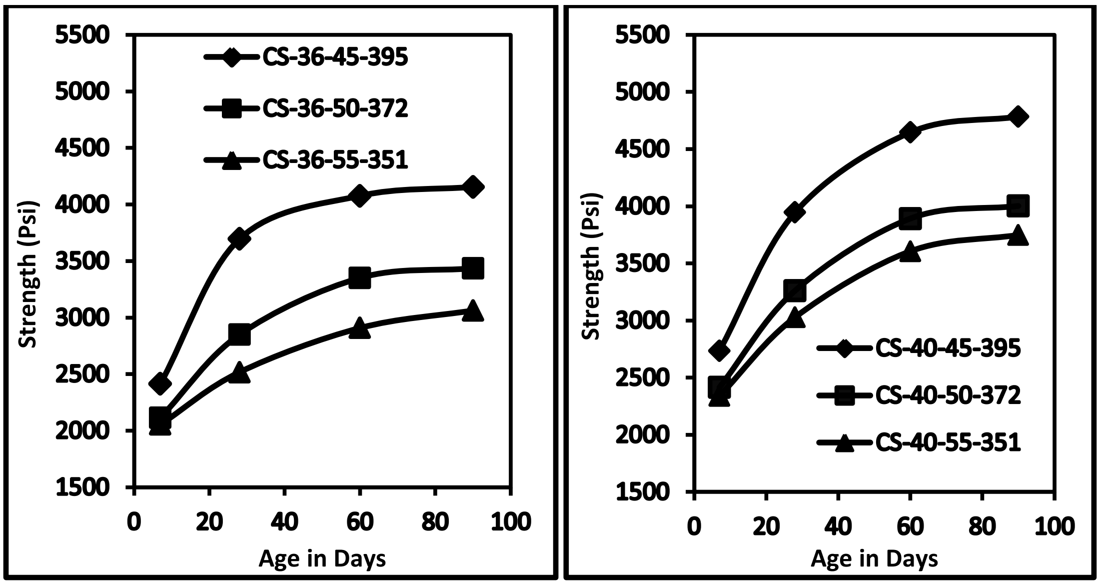
(b)



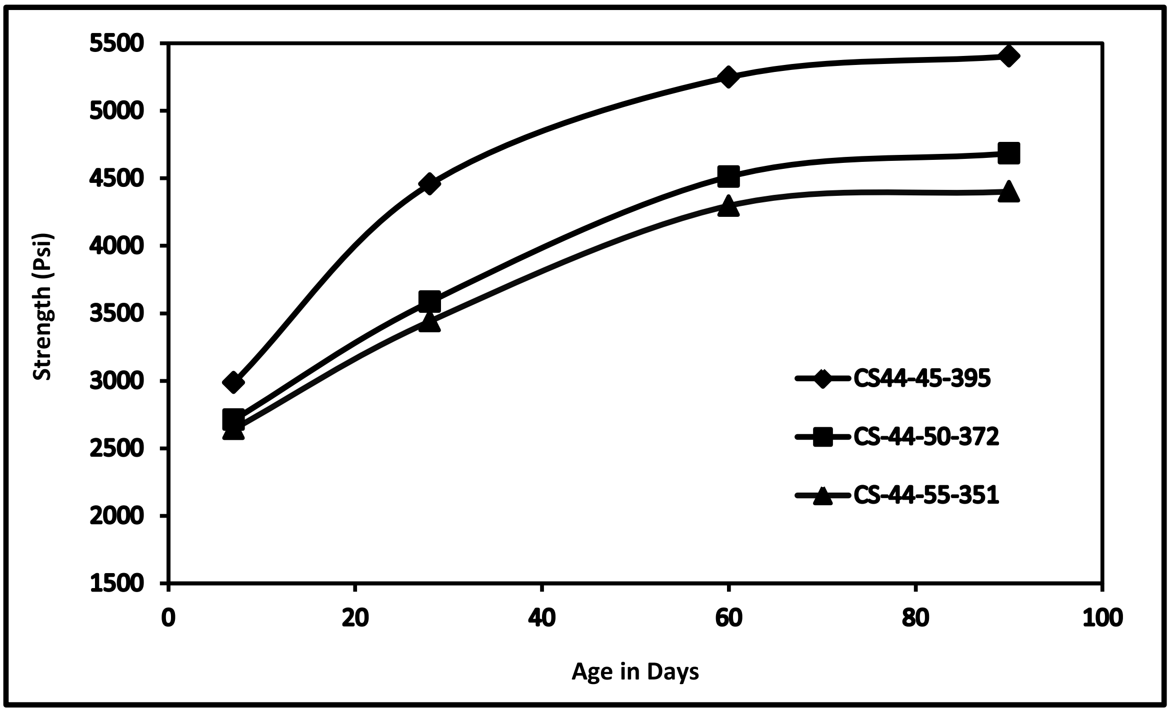
(c)

Figure : 4-19 (a, b, c) **Strength Vs Curing periods for brick**

As for concrete made with crushed stone aggregate

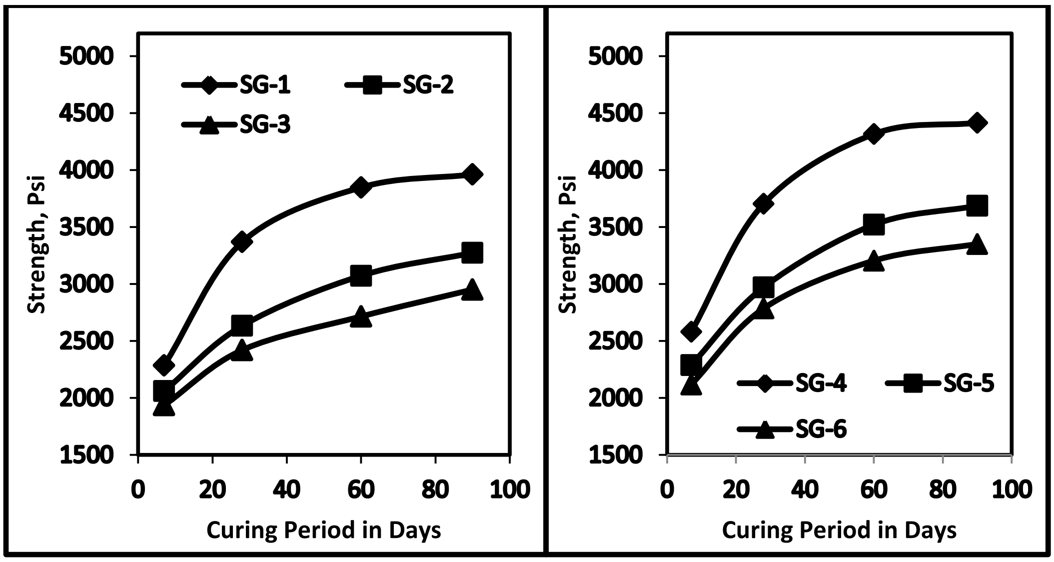


(a) (b)

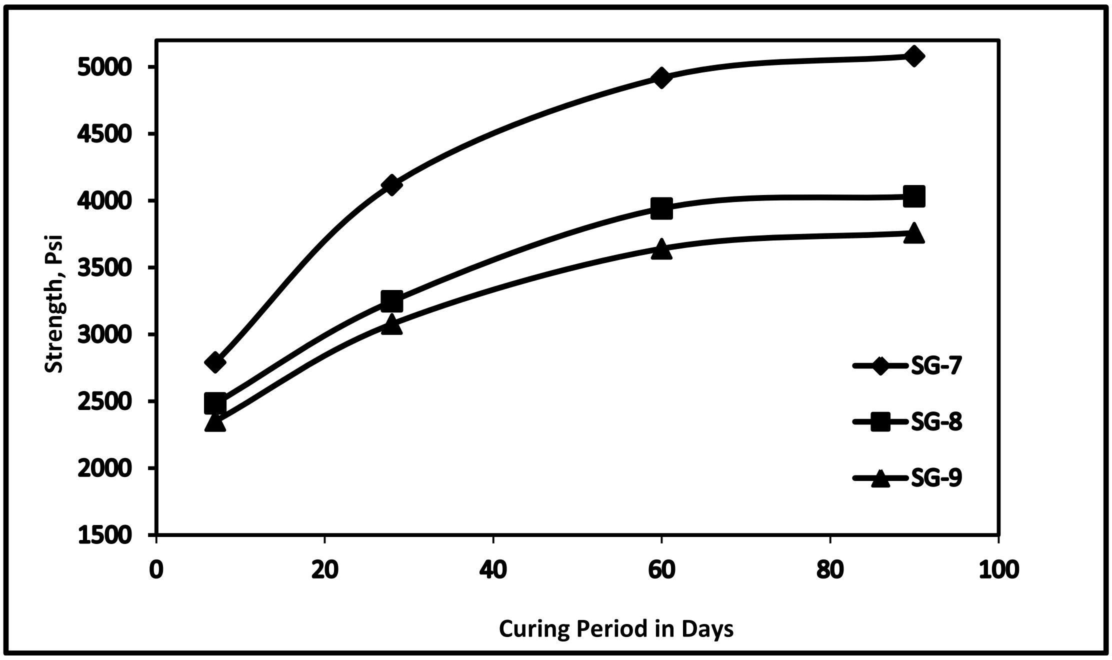


(c)

Figure: 4-20 (a, b, c) **Strength Vs Curing periods for crushed stone**

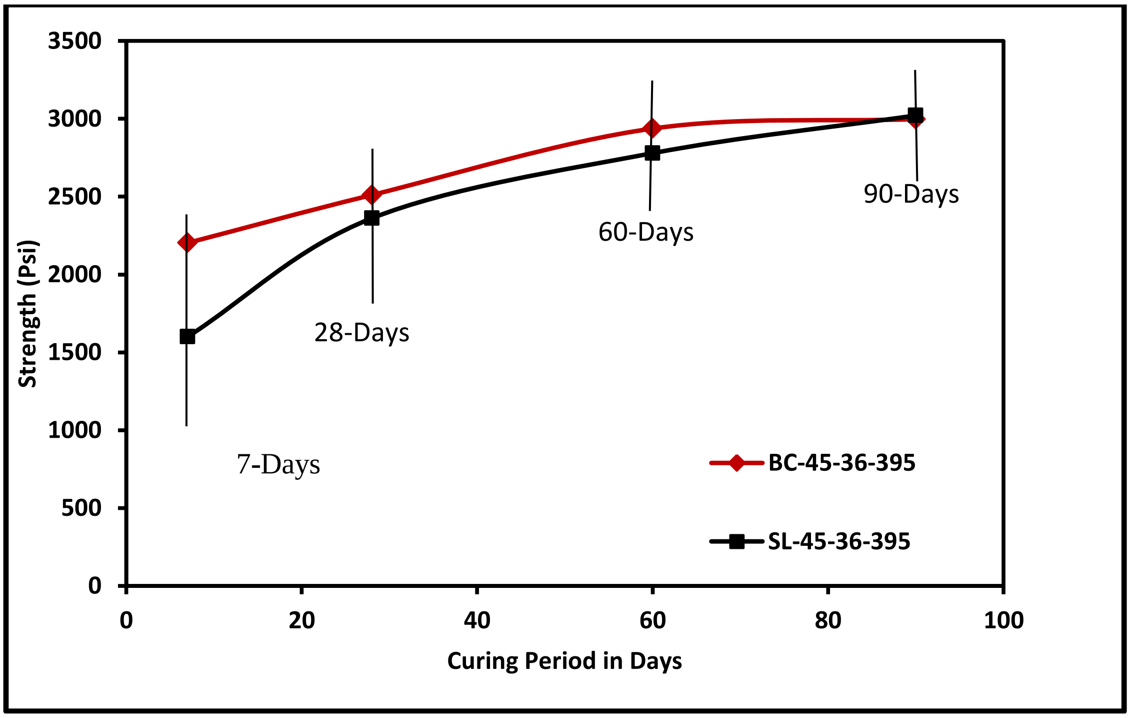


(a) (b)

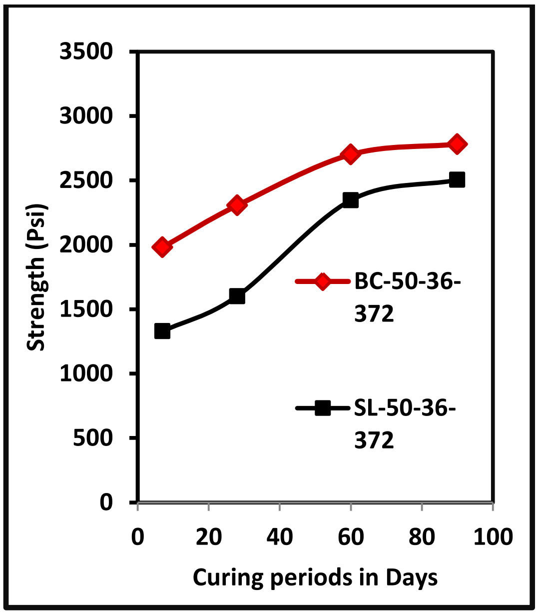


(c)

Figure: 4-21 (a, b, c) **Strength Vs Curing periods for Shingles**



(a)



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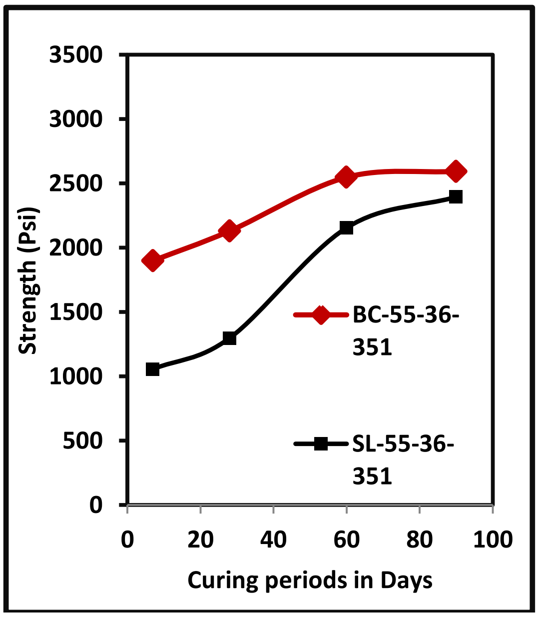
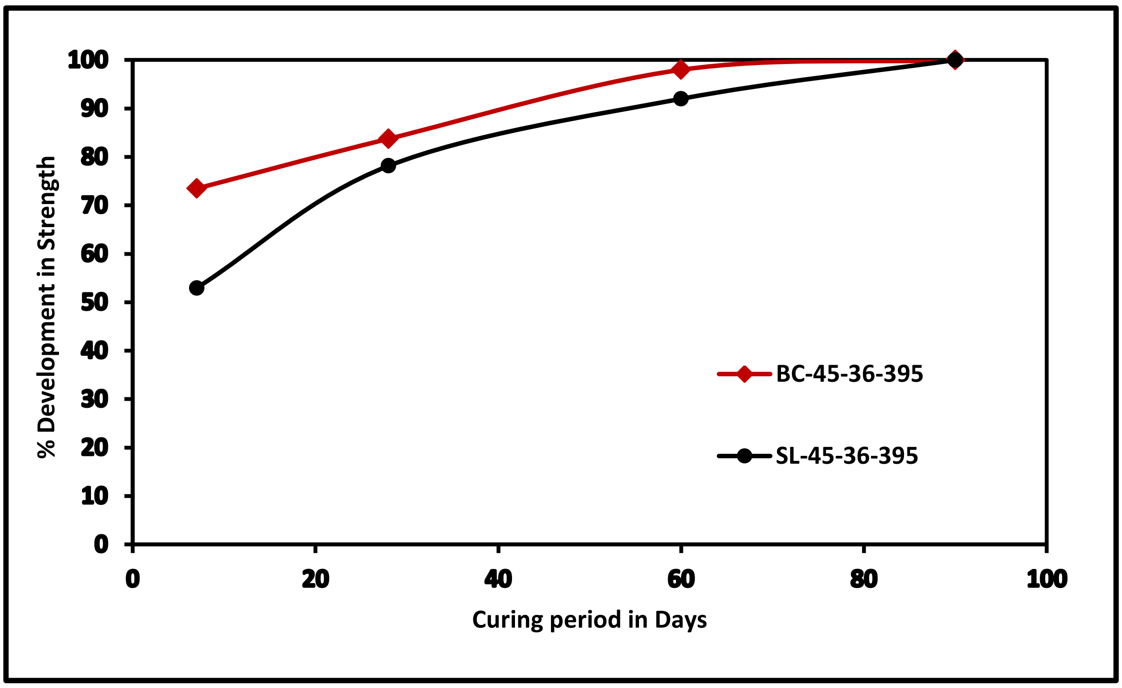
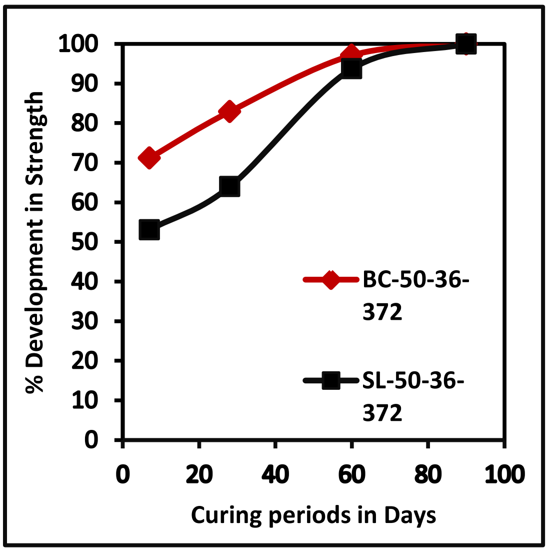


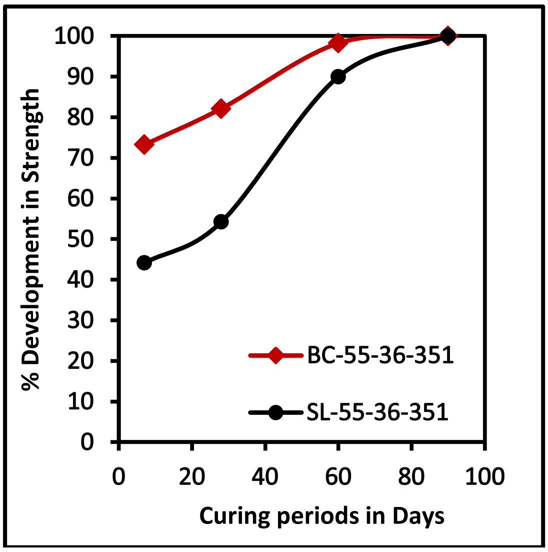
(c)

Figure: 4-22 (a, b, c) **Strength Vs Curing periods for SL and Brick**



(a)





(b) (c)

Figure: 4-23 (a, b, c) **%Development of strength comparison between SL and Brick**

From the above plots, it can be observed that all the strength vs age relationship follows usual trends. Each of the plots except plot of iron slag shows almost 50%-70% development of strength on 7-day tests. Also, 28-day test reveals that concrete specimens achieved almost 80%-85% of its ultimate strength. Although concrete specimens made with black stone aggregate, heavy slag (SH) and mixed slag (SM) are not considered here for plotting as tests are performed only for 28-days.

In addition to usual test results found out for concrete specimens made with other aggregates, light weight slag (SL), heavy slag (SH) and black stone (BS) gives curious results in terms of strength. Heavy slag shows that with a volumetric mix constituting M20 grade concrete (1:1.5:3), it is possible to achieve at least 5000Psi concrete. It suggests that with careful mix proportion high strength concrete can be prepared with this type of aggregate. Likewise, concrete made with black stone aggregate also shows high load bearing capability. For s/a ratio of 0.44, W/C of 0.45 and cement content of 395kg/m^3 it is found out that concrete made with black stone aggregate gives 4820Psi. So, it can be also addressed with a potential for preparing high strength concrete.

As for concrete made with light slag aggregate (SL), it showed a bit different finding in term of strength. The concrete is not strong enough and therefore, cannot be made with a low quality mixing. In this study, concrete made with light slag is compared with concrete made with brick chips aggregates. And it shows that it has less bearing capacity than concrete made with brick chips aggregate. Although, it is observed from the %development plot that, development of compressive strength in concrete made with light slag aggregate is much less as found out on 7-day and 28-day tests when compared to concrete made with brick aggregates. Eventually, there is 5%-10% gap in strength development with concrete made with light slag aggregate on a 60-day laboratory test.

It is clear from the plot that concrete made with iron slag has a late hydration property. It is because of the process that is followed while manufacturing steel. In the local steel manufacturing plant, induction furnace is used for steel making where the steel is treated with lime for stabilizing the product. As an outcome, the slag produced contains silica and lime which is also attributed as the primary constituents of cement. The fact suggests that it might have cementitious property when exposed to moisture. The study confirms that with age, concrete made with light slag can show a late age strength development. Further study is required in order to confirm whether it possible to replace the cement with ground granulated slag.

Variation of ultrasonic pulse velocity (UPV) with age is also analyzed for a better understanding. Although, UPV variation with age exhibits a somewhat similar trend like strength variation with age of concrete specimens, but the major difference between UPV variation and compressive strength variation can be addressed in terms of %development with age. As shown earlier, upon reaching 7-day and 28-days compressive strength tends to achieve about 50%-70% and 70%-90% of its ultimate strength. In case of UPV, almost 80%-90% and 90%-95% of ultimate velocity is reached on 7-days and 28-days respectively.

With age, different aggregate tends to follow the common trend whereas, different aggregates have different sets of physical properties. Steel slag (light) also shows distinctive behavior when analyzed with ultrasonic pulse velocity. As it has been stated that steel slag is an outcome of steel industry, it contains significant amount of iron content for an aggregate. So, when exposed to UPV, concrete made with steel slag shows a faster UPV count than concrete made with other aggregates. Also due to late hydration property of light weight steel slag aggregate, we see a sudden rise in UPV at later age.

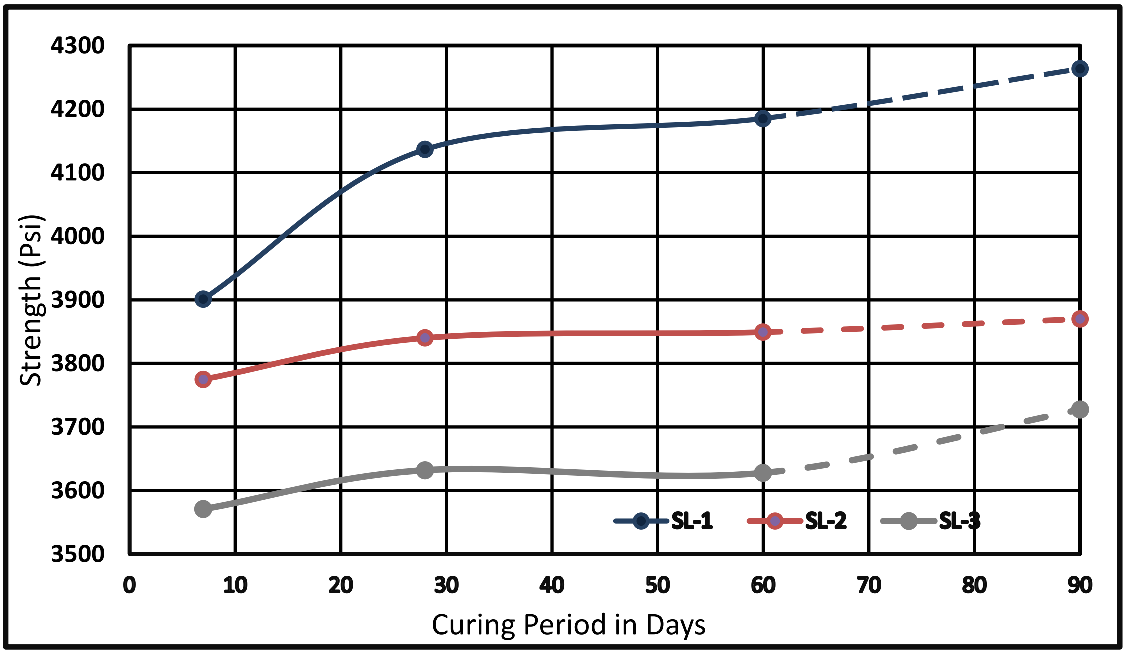
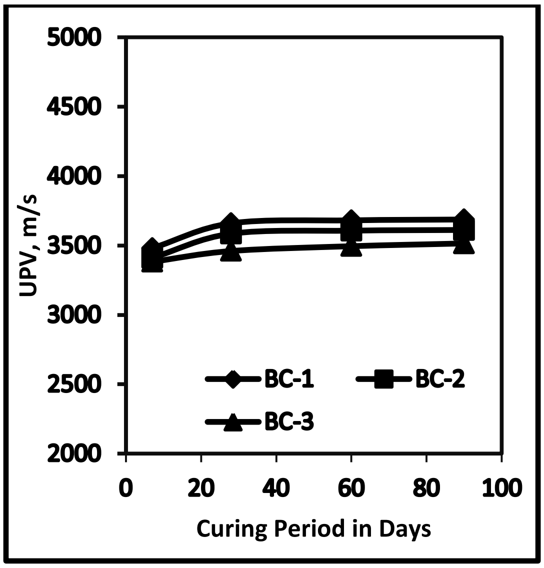
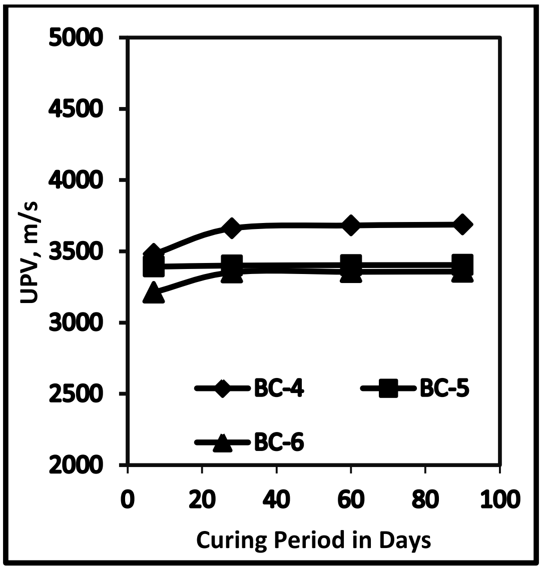


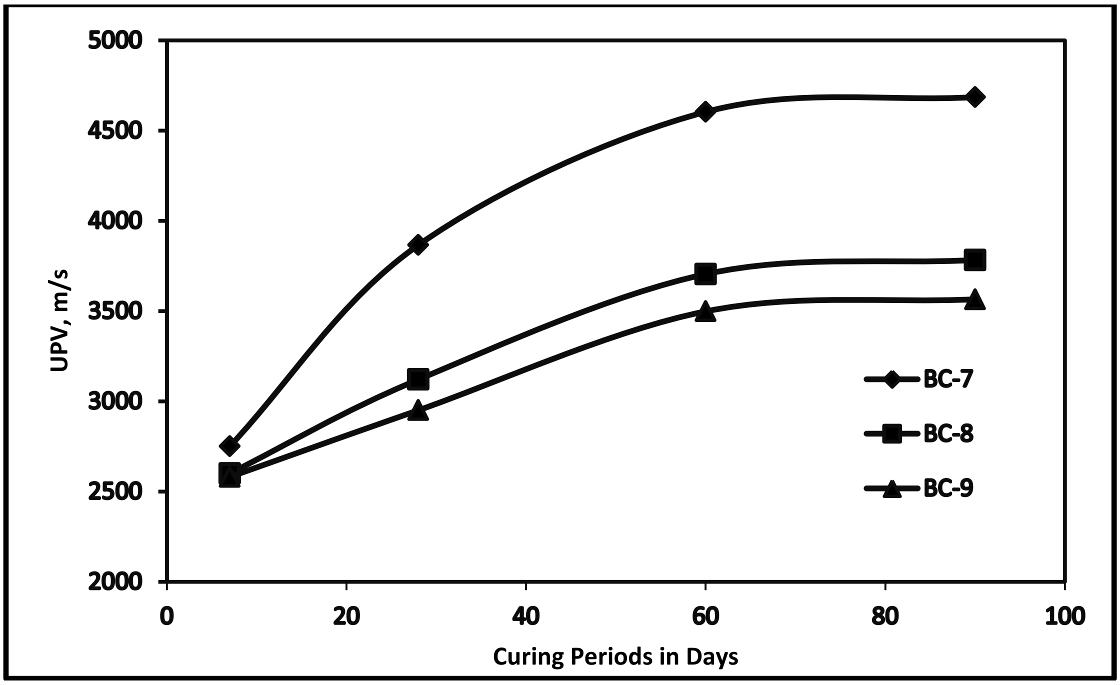
Figure: 4-24 **Strength development of *SL* at later stage (Late hydration)**



(a)

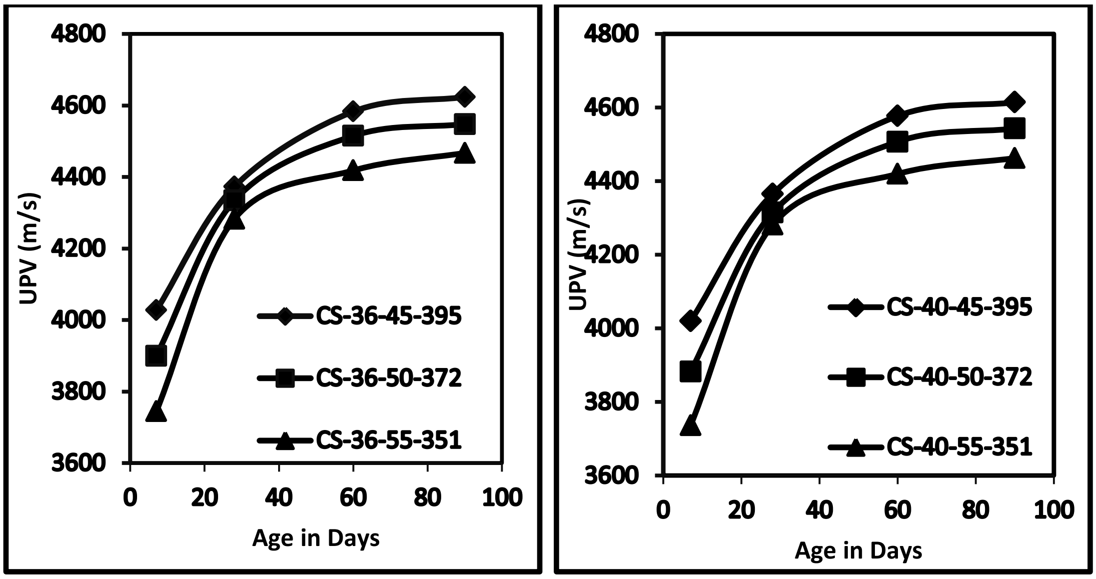


(b)

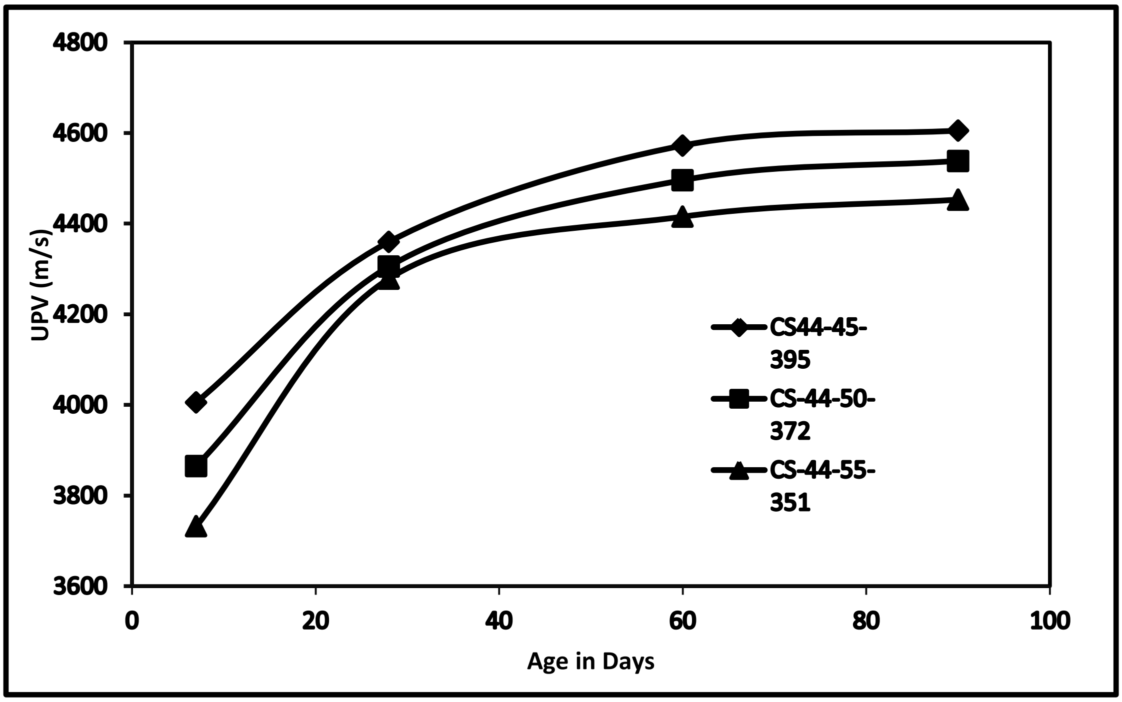


(c)

Figure: 4-25 (a, b, c) **Relationship between UPV and Curing period of Concrete (Brick)**

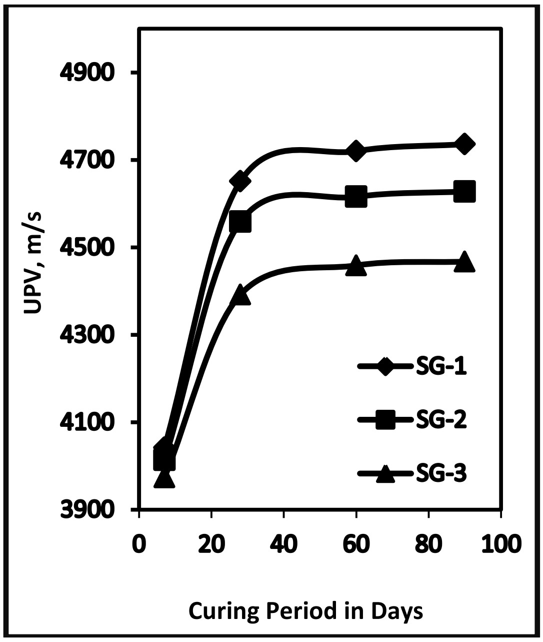


(a) **(b)**

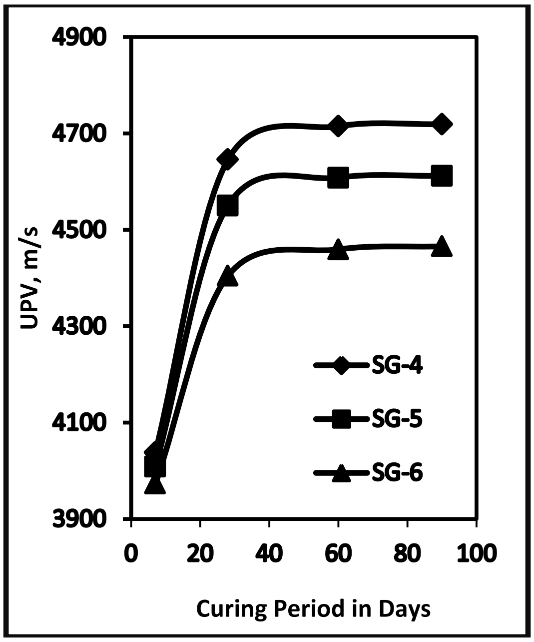


(c)

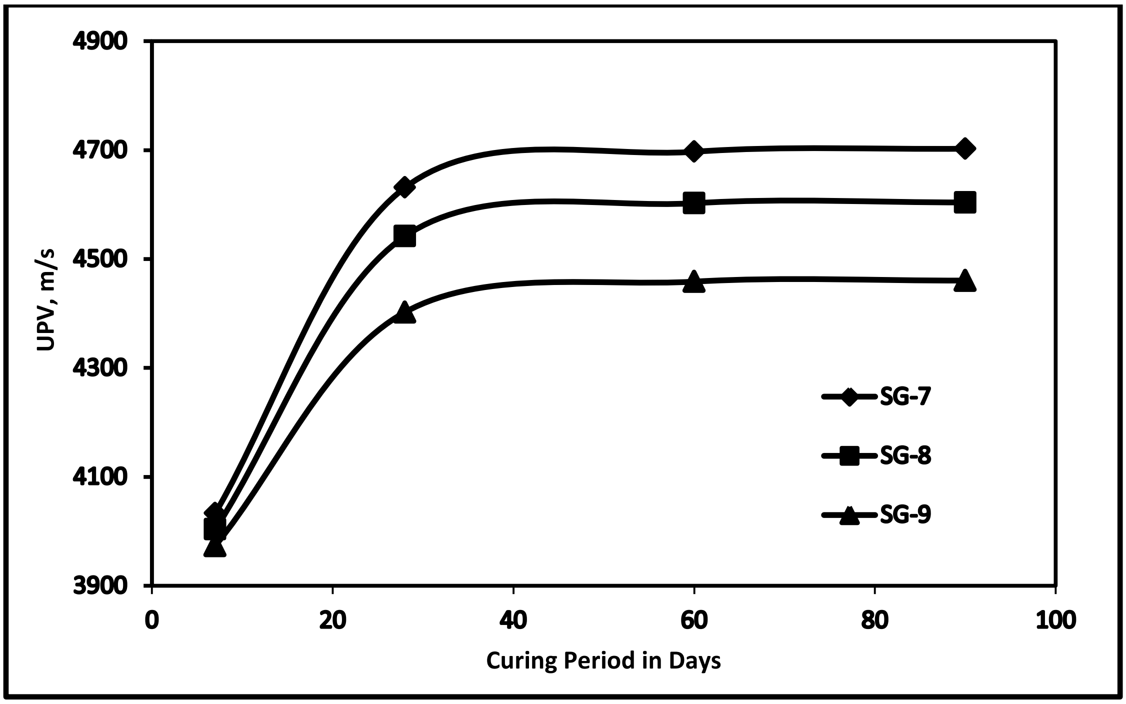
Figure: 4-26(a, b, c) **Relationship between UPV and Curing period of Concrete (Crushed Stone)**



(a)



(b)



(c)

Figure: 4-27 (a, b, c) **Relationship between UPV and Curing period of Concrete (Shingles)**

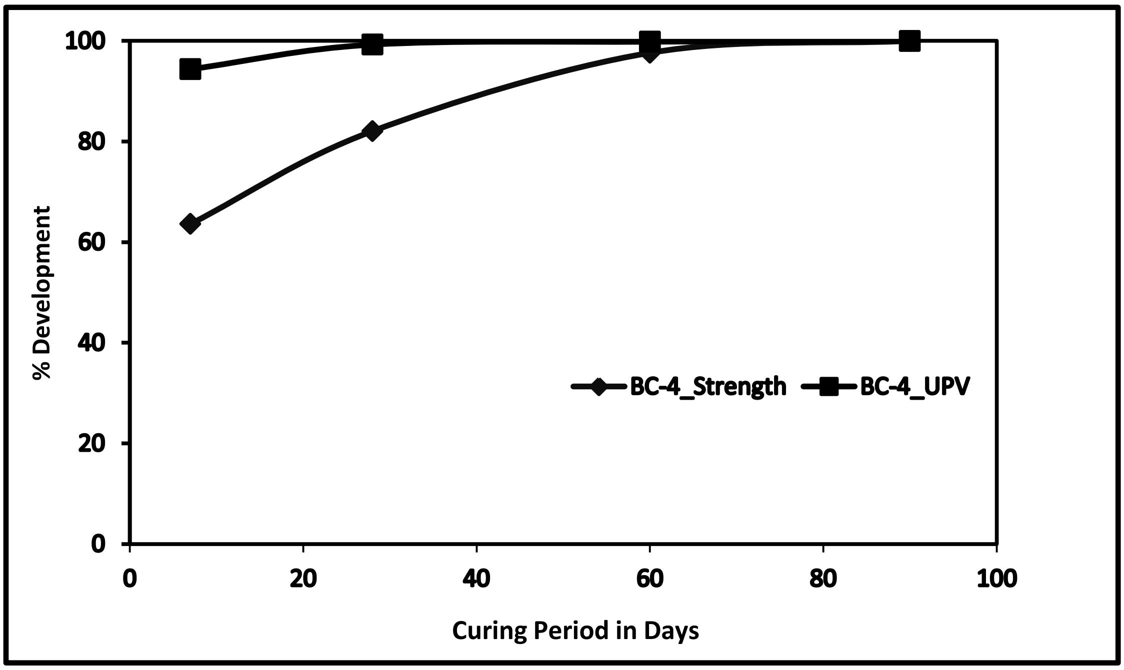


Figure: 4-28 **Analysis of % Development in strength and UPV for Concrete (Brick)**

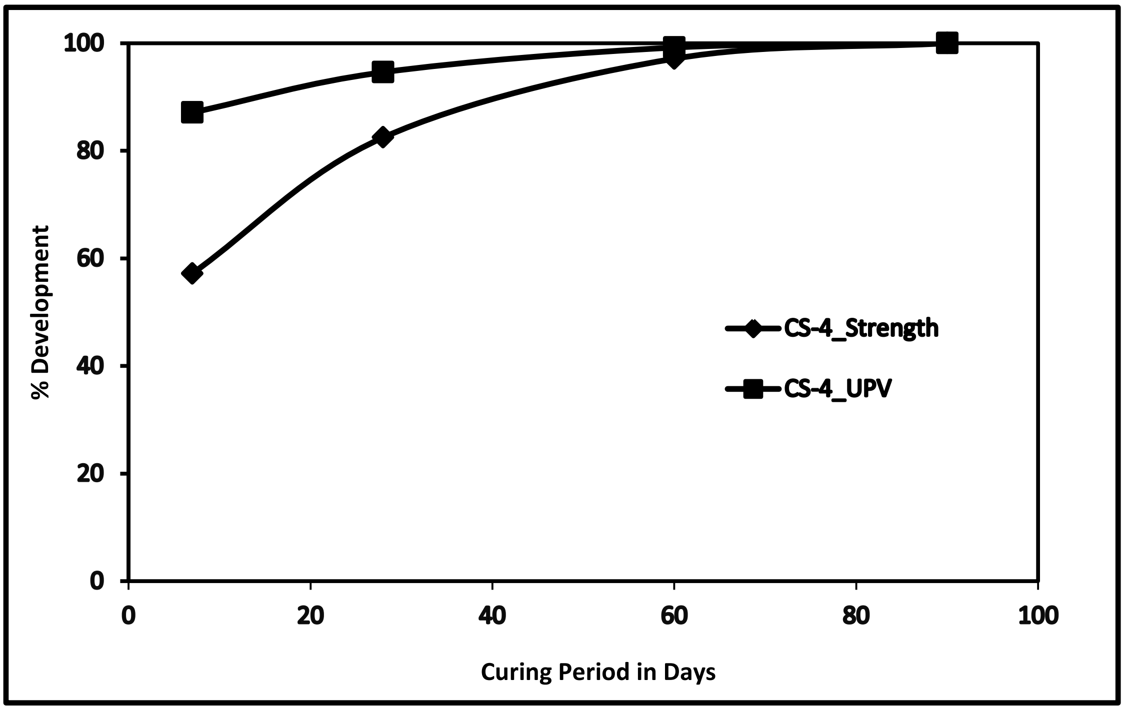


Figure: 4-29 **Analysis of % Development in strength and UPV for Concrete (Crushed Stone)**

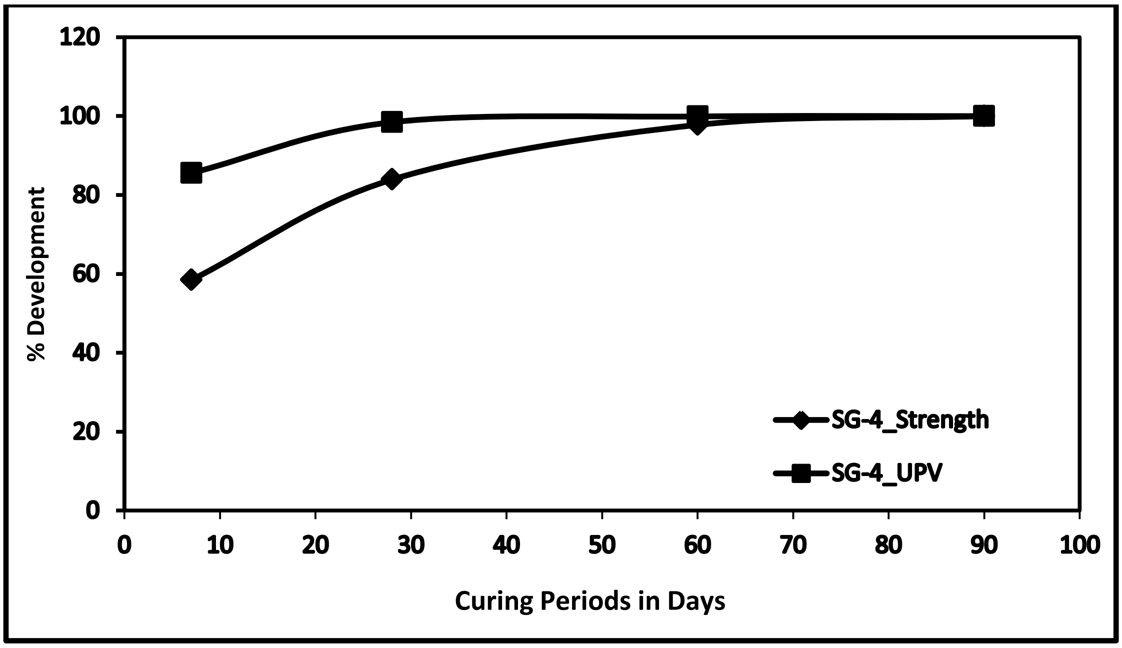
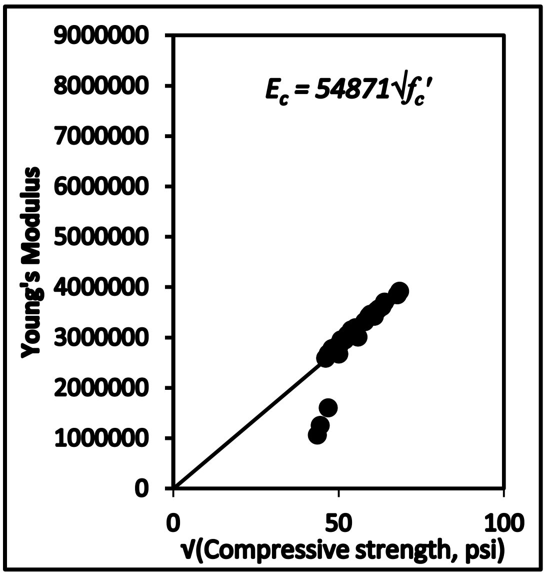


Figure: 4-30 **Analysis of % Development in strength and UPV for Concrete (Shingles)**

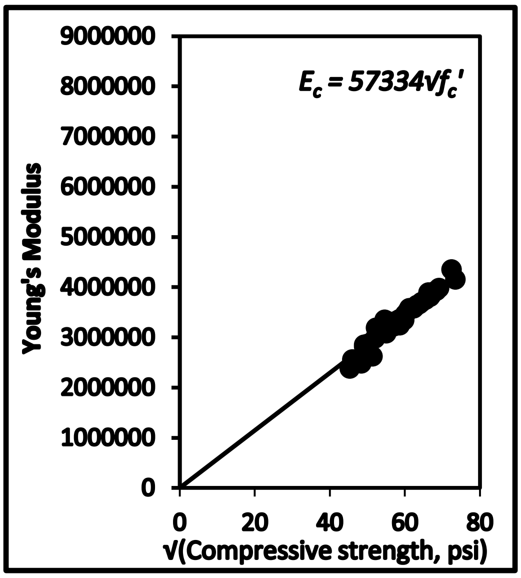
4.7 Young's Modulus

Young's modulus has been found out for concrete specimen made with each of the aggregate tested in order to analyze their behavior under applied stress. As young's modulus is an indicator of how elastic the concrete is, thus it very important in order to understand the behavior of concrete made with particular type of aggregate. From following figures it can be observed that concrete made with brick chips aggregate has the lowest recorded young's modulus. Although, much higher E_c are recorder for black stone and light weight slag (SL).

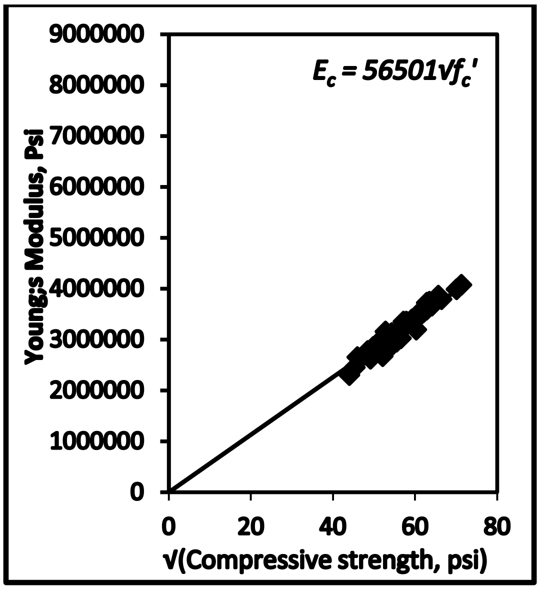
Although light weight slag (SL) has less load bearing capacity than any other materials, its E_c is significantly higher. The reason behind this can be attributed as the better aggregate-mortar bonding which does not allow much deformation at early stage of loading. But, as the aggregate itself is not much strong enough eventually the concrete specimens fail due to heavy loading exhibiting a combined failure. So, as for concrete made with light slag (SL) can be concluded as a brittle material.



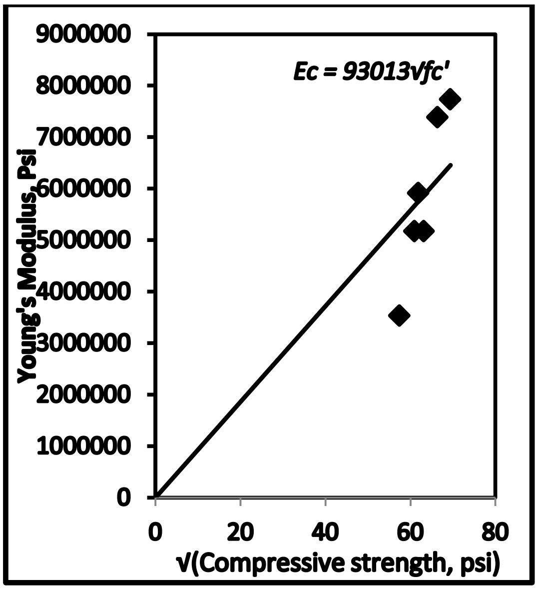
(a) Brick



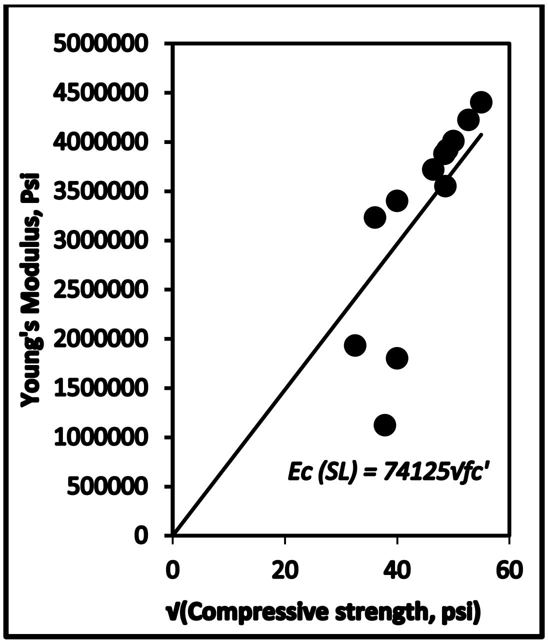
(b) Crushed Stone



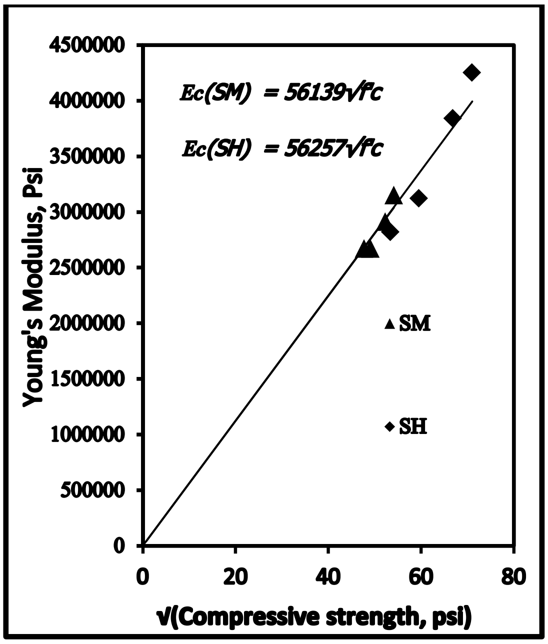
(c) Shingles



(d) Black Stone

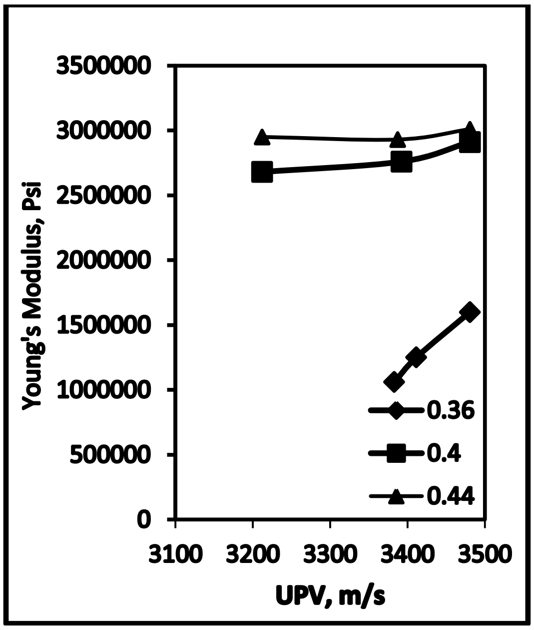


(e) Light Slag (SL)

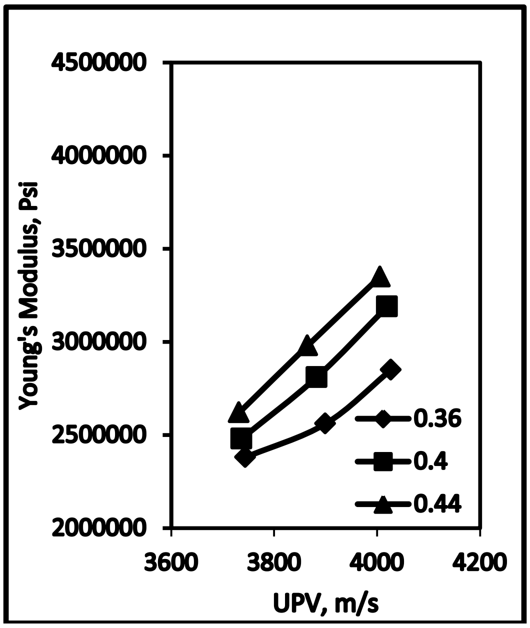


(f) Mixed Slag and Heavy Slag

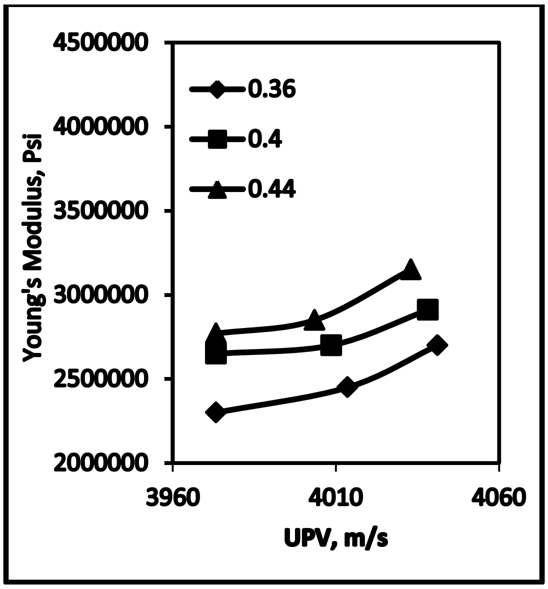
Figure: 4-31 (a, b, c, d, e, f) ***Young's Modulus Vs.*** √ ***(Compressive strength)*** **Plot**



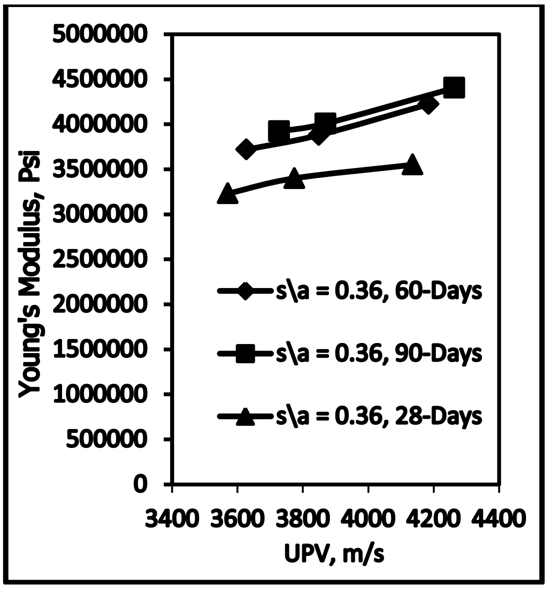
(a) Brick



(b) Crushed Stone



(c) Shingles



(d) Light Slag (SL)

Figure: 4-32 (a, b, c, d) **Relationship between Young's Modulus vs. UPV for various Concrete**

Also, concrete made with black stone has a very high E_c value indicating high elasticity. It is observed that its elastic range is much higher than plastic range. The aggregate itself has a very high specific gravity along with high unit weight. Also, the aggregate has very good bonding with mortar, thus exhibiting higher young's modulus. Concrete made with shingles shows less E_c value when compared to concrete made with crushed stone. This is due good interlocking properties of crushed stone aggregate promoting better compaction and less bleeding giving better E_c value.

The following relationships are proposed between Young's modulus (E_C) and compressive strength of concrete (f'_c) made with different aggregates:

For brick chips aggregate $$E_C = 54871\sqrt{f'_C} \quad (1)$$

For crushed stone $$E_C = 57334\sqrt{f'_C} \quad (2)$$

For shingles $$E_C = 56501\sqrt{f'_C} \quad (3)$$

For black stone $$E_C = 93013\sqrt{f'_C} \quad (4)$$

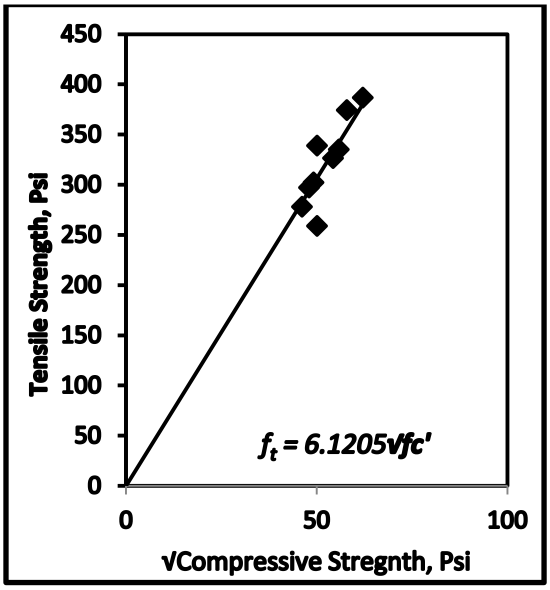
For light slag (SL) $$E_C = 74125\sqrt{f'_C} \quad (5)$$

For mixed slag (SM) $$E_C = 56139\sqrt{f'_C} \quad (6)$$

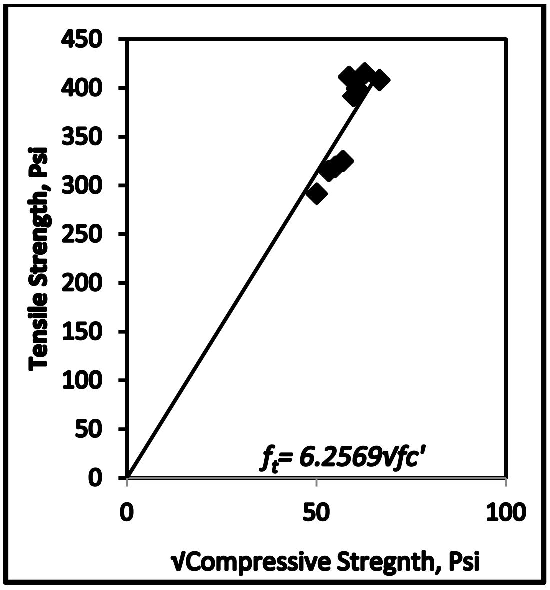
For heavy slag (SH) $$E_C = 56257\sqrt{f'_C} \quad (7)$$

4.8 Tensile Strength

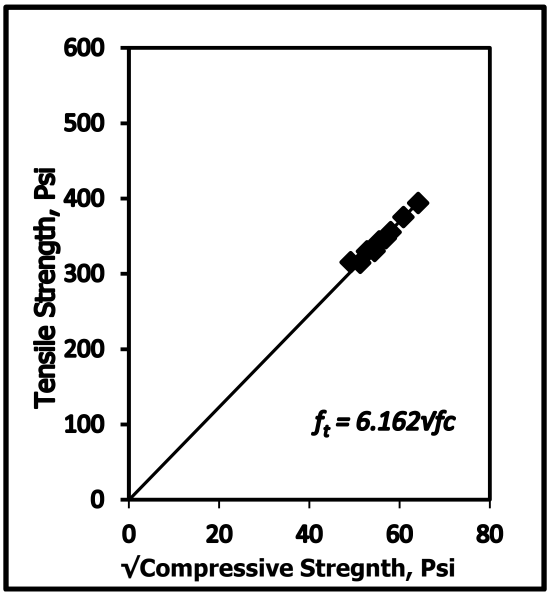
Tensile tests for concrete made with different types of aggregate are done for each type of aggregate tested at 28-days. Tensile strength test revealed that concrete made brick chips aggregate shows least strength among concrete made with other aggregate. Although concrete made with crushed stone has more tensile strength than concrete made with shingles. The reason is stated as before that the interlocking properties of crushed stone aggregate, higher compaction and less bleeding. Also, it can be observed that concrete made with the lightweight slag aggregate (SL) shows lower tensile strength compared to the similar concrete made with brick aggregate, however concrete made with SM and SH show higher tensile strength compared to the similar concrete made with brick aggregate. It is also found that with the increase in cement content, the tensile strength of slag aggregate concrete is increased. f_t Tensile strength of concrete is analyzed by plotting tensile strength against square root of f_c' as follows:



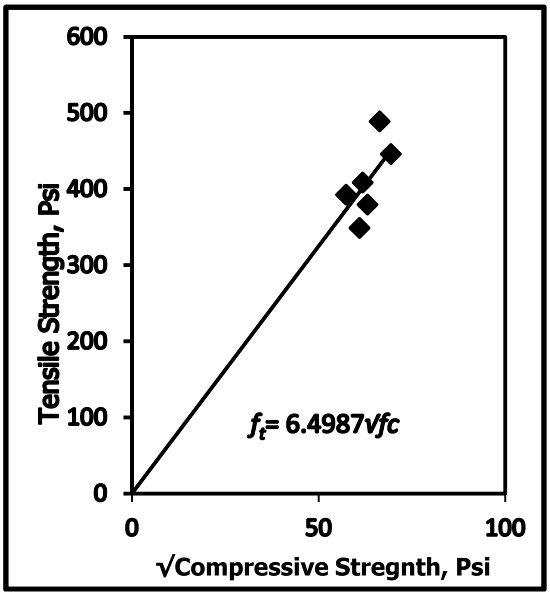
(a) Brick



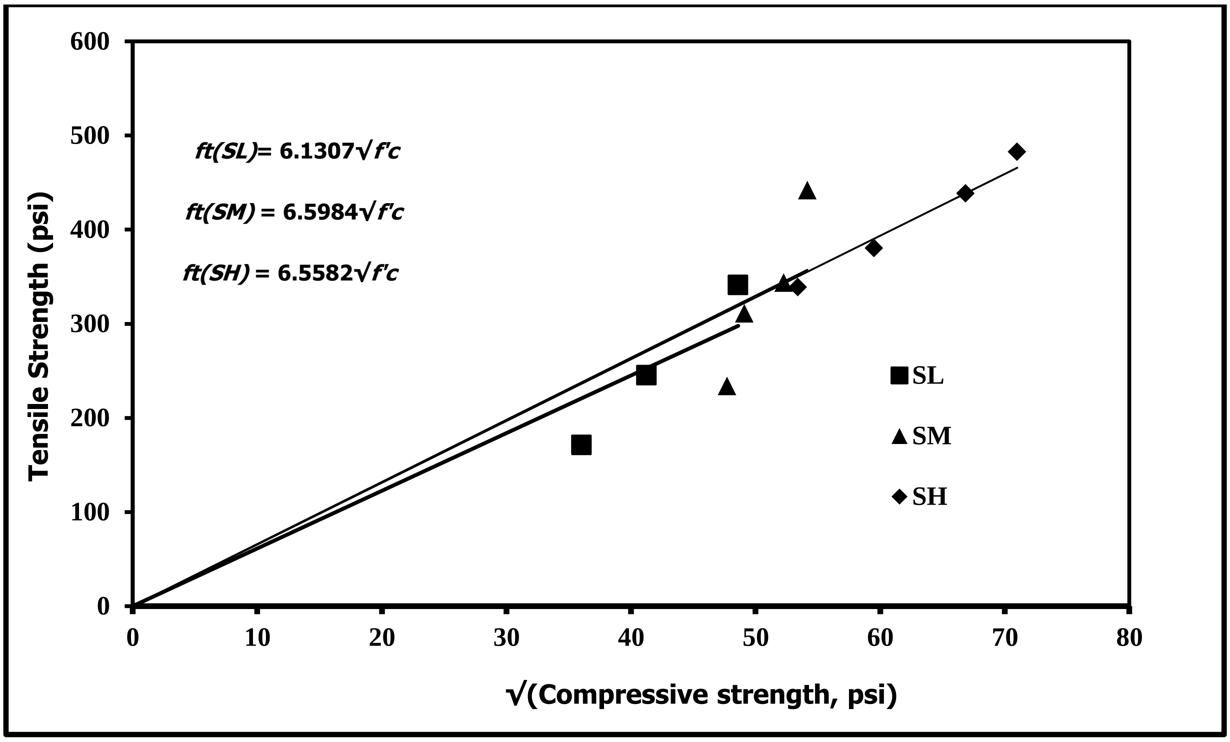
(b) Crushed Stone



(c) Shingles



(d) Black Stone



(e) Iron Slag (SL, SM, SH)

Figure 4-33 (a, b, c , d, e) **Tensile Strength vs. √(Compressive strength, psi)**

The following relationships are proposed between tensile strength (f_t) and compressive strength (f'_c) of concrete made with different aggregates:

For brick chips aggregate $f_t = 6.1205\sqrt{f'_C}$ (8)

For crushed stone $f_t = 6.2569\sqrt{f'_C}$ (9)

For shingles $f_t = 6.162\sqrt{f'_C}$ (10)

For black stone $f_t = 6.4987\sqrt{f'_C}$ (11)

For light slag (SL) $f_t = 6.1307\sqrt{f'_C}$ (12)

For mixed slag (SM) $f_t = 6.5984\sqrt{f'_C}$ (13)

For heavy slag (SH) $f_t = 6.5582\sqrt{f'_C}$ (14)

4.9 Conclusion

The primary goal of this study was to find out and establish relationship between ultrasonic pulse velocity and compressive strength of concrete. Also, brief analysis with an attempt to establish link between different properties of concrete and UPV was also done. Comprehensive study among concrete made with different types of aggregate are made in order to have a better understanding.

Chapter 5 Conclusion

5.1 Reviews on Completed Research Work

As per the objective and scope of the study to find out a suitable relationship between compressive strength of concrete and UPV, different relationships are found out on the basis of the sand to total aggregate volumetric ratios. Also different options are explored to find out possible relationship between UPV and other properties of concrete e.g. Young's modulus.

In this chapter the findings of these tests will be mentioned in a short way to highlight the main points related to the study.

5.2 Summary and Conclusion

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

1. Ultrasonic pulse velocity count for concrete depends on the type of aggregate being used.
2. Ultrasonic pulse velocity of concrete depends on the volumetric s/a ratio.
3. Ultrasonic pulse velocity of concrete depends on the age of concrete specimen.
4. Ultrasonic pulse velocity of concrete depends on the compressive strength of concrete.
5. Ultrasonic pulse velocity depends on the texture of the aggregate being used. If the surface texture is strong then UPV count will be higher.

6. Ultrasonic pulse velocity of concrete depends on the void between aggregates, degree of compaction.
7. Ultrasonic pulse velocity tends to decrease with higher s/a ratio where strength tends to increase with higher s/a ratio.
8. Ultrasonic pulse velocity depends on the acoustic impedance of the aggregate being used.
9. A possible linkage is found between ultrasonic pulse velocity of concrete and young's modulus (E_c).
10. With increasing s/a ratio, the number of uniform interfaces in the concrete specimen decreases. As a result, UPV also decreases. So, Ultrasonic pulse velocity depends on the uniform uninterrupted interfaces in the concrete.

5.3 Recommendation for Future Studies

Based on the drawn out summaries, following recommendations can be made:

1. Effect of variation of volumetric cement paste content (%Paste) is to be explored.
2. Effect of variation of maximum size of aggregate on UPV is to be found out.
3. Effect of wide range of s/a ratio on UPV is to be explored.
4. Effect on commercially used retarders on UPV can be experimented.
5. Effect of different type of cements on UPV can be explored.
6. Effect of temperature on UPV can be explored.
7. For processed steel slag, different mix ratios can be tried to find out the effect on compressive strength of concrete.

8. For light weight steel slag, late hydration property is to be tested in a much more detail manner.
9. Partial replacement of steel slag with commonly found aggregates can be tested.

Effect of ground slag as a cementitious material can be tested to find out whether it is possible to partially replace the cement.

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