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Ultrasonic Pulse Velocity Investigation of Steel Fiber Reinforced Self-Compacted Concrete

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ULTRASONIC PULSE VELOCITY INVESTIGATION OF STEEL FIBER REINFORCED SELF-COMPACTED CONCRETE

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ABSTRACT

Ultrasonic Pulse Velocity Investigation of Steel Fiber Reinforced Self-Compacted Concrete

Concrete is a basic material used for a number of applications in civil engineering projects. Structural concrete is brittle material under normal conditions. Therefore, by adding short and randomly distributed steel fibers, it is possible to improve the ductility and other basic properties of concrete. However, the addition of steel fibers results in loss of workability of the concrete, especially in self-compacted concrete. Therefore, in this study, ADVA-140 high range water reducer (HRWR) superplasticizer was added to improve the workability of self-compacted (SC), steel-fiber-reinforced concrete (SFRC). The amount of superplasticizer varied with the volume percentage of fiber for the beams; however, it was kept constant for the cylinder, as shown in Tables 4-2 and 4-3, respectively. Other admixtures, such as fly ash and silica fumes, were also added to improve the concrete properties. Type II deformed steel fibers with a diameter of 0.023 in and length of 0.75 in were added to the mix. The amount of steel fibers varied from 0-4% for the beam samples and from 0-2% for the cylinder samples. The samples were self-compacted to allow for self-setting without applying vibration in order to avoid materials segregation and bleeding.

A total of 18 beam samples and 5 cylindrical samples were investigated in this experiment. The ultrasonic pulse velocity (UPV) method was applied to detect flaws and characterize the properties steel fiber reinforced self-compacted concrete. This method is used to measure the time required for the ultrasonic wave to travel through the test material and energy attenuation. Knowing the time of flight, it is possible to calculate the wave velocity through the material. This study investigated the effects of steel fiber volumes, curing periods, wet and dry conditions (saturation), and fiber and aggregate orientations on UPV. The result showed that by controlling measurement errors and environmental factors, the UPV is a very promising method to detect concrete flaws and to estimate design properties in concrete structures.

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DEDICATION

To my family:

Thank you for always standing with me.

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CHAPTER 1

INTRODUCTION

1.1 General

Concrete is used extensively in most civil engineering constructions, and its application is even increasing. The reason is because its constituent materials are locally available, it has high compressive strength, and it has relatively low cost for the required strength (ACI 544.1R, 1996).

Concrete is a brittle material which may fail without a warning signal under peak compressive force. Therefore, improving the ductility and strain capacity of concrete is very important. By far, a pre-designed and continuous steel bars have been embedded into the concrete to resist the tensile force imposed on the structure. Unlike the continuous reinforcing steel bars, steel fibers are added to the concrete randomly to improve its ductility and crack control capacity. "It is important to recognize that, in general, fiber reinforcement is not a substitute for conventional reinforcement" Behbahani (2010).

The steel fiber reinforced high strength concrete (SFRHSC) samples were used in this experiment. The samples were provided by Dr. S. Ladkany and Mr. Abebe Berhe (PhD) student, prepared for the ongoing research on steel fiber reinforced self-compacted high strength concrete at University of Nevada, Las Vegas (Berhe and Ladkany, 2011; Ladkany and Berhe, 2013a and 2013b). Therefore, this research was performed on the readymade samples to characterize them using ultrasonic pulse velocity method which is different from the ongoing research. The samples were allowed to consolidate with their own weight to avoid steel fiber and aggregate segregations and bleeding.

The addition of steel fibers reduces the workability of fresh SCC mixes. However, adding superplasticizer improves its workability. Other fine materials such as fly ash and silica fumes were added to the mix to fill the micro voids within the mix and to get denser and stronger test samples. The samples tested in this study have a strength in compression of approximately 12,000 psi which classifies them as high strength concrete (Berhe and Ladkany, 2013a, and Berhe and Ladkany, 2013b).

Ultrasonic pulse velocity (UPV) non-destructive test method was employed in this experiment to characterize the steel fiber reinforced self-compacted high strength concrete. The UPV utilizes the compressional wave generated by a sophisticated transducer in contact with the test sample. The wave propagates through the test materials and detected by the receiving transducer. The wave travel time and energy decay through the material has been processed and displayed by the digital computer.

1.2 Problem Statement

Even though, the application of ultrasonic pulse velocity for materials characterization started three decades ago, its behaviors through steel fiber reinforced self-compacted concrete have not been identified yet.

1.3 Thesis Objective

The main objective of this study is to investigate the behaviors of ultrasonic pulse velocity through steel fiber reinforced self-compacted concrete with respect to volume fraction of steel fibers, curing periods (7 days, 28 days, and 90 days), steel fiber and aggregate orientations, and wet/dry conditions.

1.4 Hypothesis

- The addition of steel fibers up to a certain amount in self-compacted concrete can increase the ultrasonic pulse velocity.
- The addition of steel fibers can reduce the workability of self-compacted concrete; hence, initiates the development of voids.
- The addition of superplasticizer was assumed to handle the poor workability caused by steel fibers.

1.5 Scope of Study

The scope of this study is to achieve the main objective, and is mainly based on experimental works. Experiments on both plain and steel fiber reinforced self-compacted concretes (SFR-SCC) with various admixtures were carried out using an ultrasonic pulse velocity (UPV) method to achieve the intended objective.

1.6 Structure of Thesis

This report consists of six chapters. Chapter 1 describes fiber reinforced concrete and introduces the problem statement, objective, hypothesis, and scope of the study. Chapter 2 emphasizes a literature review of SFRC and UPV tests. The details of the methodology employed in this study are discussed in Chapter 3. Chapter 4 focuses on materials and the experimental program used in this study. Chapter 5 is mainly about the results and discussions of the experiment. Finally, conclusions and recommendations are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

There are few studies on ultrasonic pulse velocity characterization of steel fiber reinforced concrete but they are not self-compacted. Therefore, it was difficult for this study to compare results with the literature findings. However, to get an insight for the responses of ultrasonic pulse velocity with respect to various factors, some relevant literature reviews were assessed.

2.1 Backgrounds of Steel Fiber Reinforced Concrete (SFRC)

Concrete is one of the most widely used construction materials. The main reason behind the wide applicability of concrete as a construction material is its high compressive strength and easy availability of its component materials almost everywhere. However, experience shows that concrete is weak in tension due to its brittle nature; that causes a sudden structural collapse without warning signs (ACI 544.1R-1996). Thus, concrete requires some means to improve ductility and strain capacity. Steel bars have been used in concrete as a reinforcement to resist the tensile forces by placing them in the concrete sections where these forces are concentrated.

Steel fiber reinforced concrete (SFRC) is a composition of hydraulic cement, fine aggregates, coarse aggregates, water, and short and discontinuous steel fibers. The properties of SFRC are a cumulative effect of the component materials. Steel fibers have a higher tensile strength than concrete. SFRCs have been used for a variety of civil engineering works including but not limited to, road, slab, heat resistant structures and other concrete products. The addition of steel fibers in a concrete matrix reduces its workability. Therefore, by adding high-range water reducing (HRWR) superplasticizer, it is possible to improve the workability of SFRC (Ramakrishnan, Coyle, Kopac, & Pasko, 1981).

2.2 Backgrounds of Ultrasonic Pulse Velocity (UPV)

Ultrasonic pulse velocity (UPV) is one of the most applicable non-destructive test (NDT) methods of concrete characterization. The ultrasonic wave is generated by a more sophisticated transducer in contact with the test material either in the form of compressional wave or shear wave. These waves are detected by the second transducer placed on the other face of the test material. The ultrasonic wave velocity depends on the elastic properties and density of the concrete (ACI 544.1R, 1996). The travel time and energy decay through the material have been processed and displayed by the digital computer connected with the transducers. Using the travel time and measured dimension, the ultrasonic pulse velocity has been calculated.

2.3 Factors Affecting UPV Test

Although the UPV method is an effective and efficient technique of characterizing concrete properties, a number of factors affect the result. Those factors may arise from two perspectives: 1) the concrete behavior itself and 2) technical errors (Malhotra & Carino, 2004). Technical errors are those caused by inappropriate use of transducers for example, mis-alignment of transducers, variable pressure applied on the two transducers, placing the transducers on rough surface and incorrect interpretations. They can be avoided by proper applications. On the other hand, those factors caused by concrete behavior are listed as follows.

2.3.1 Aggregate Size and Type

Many investigators have found that the size and type of aggregate significantly affects the UPV (Malhotra & Carino, 2004). Therefore, the influence of aggregate should be considered for accurate prediction of concrete properties using UPV. Studies by Jones (1962) and Trtnik, Kavcic and Turk (2009) indicated that for the same strength level, concrete having higher aggregate content resulted in higher pulse velocity value. Berriman, Purnell, Hutchins, and Neild (2005) have shown there is a strong relation between concrete aggregate content and speed of sound. Moreover, Trtnik et al. (2009) concluded that the amount of aggregate does not affect the UPV and concrete strength to the same degree. That is, the UPV is more sensitive than strength for variations of aggregate size and type. Jones (1954) reported that, for the same mixture and compressive strength, concrete with rounded gravel had the lowest pulse velocity, crushed limestone had the highest pulse velocity, and crushed granite resulted in an intermediate value.

2.3.2 Water-Cement Ratio (w/c)

Ye, Lura, Van Breugel, and Fraaij (2004) studied concretes with different amounts of water/cement (w/c) ratios (0.4, 0.45 and 0.55); they concluded that the mixes with lower w/c ratios had higher values of UPV, which could be associated with the higher amount of solids in the mixes (Fig. 2-1). On the other hand, mixes with lower w/c ratios had more aggregate content, which in turn increased the pulse velocity.

Kaplan (1959) reported that the effect of w/c on UPV is more pronounced at later ages of hydration, when the volume of capillary pore is reduced. Similarly, he studied the effects of the water/cement (w/c) ratio on the pulse velocity test and found that when w/c increased, the compressive and flexural strengths and the corresponding UPV decreased keeping all other parameters constant.

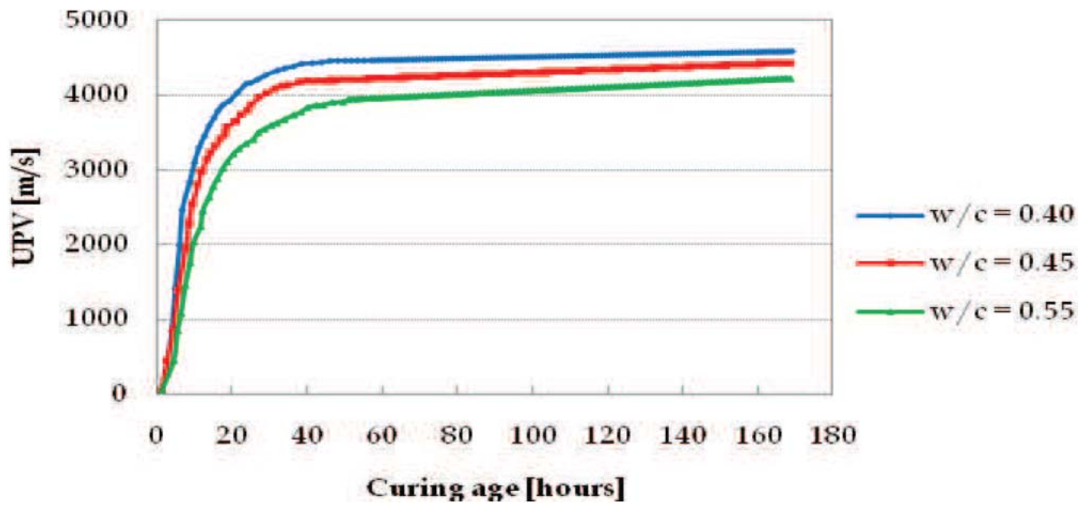


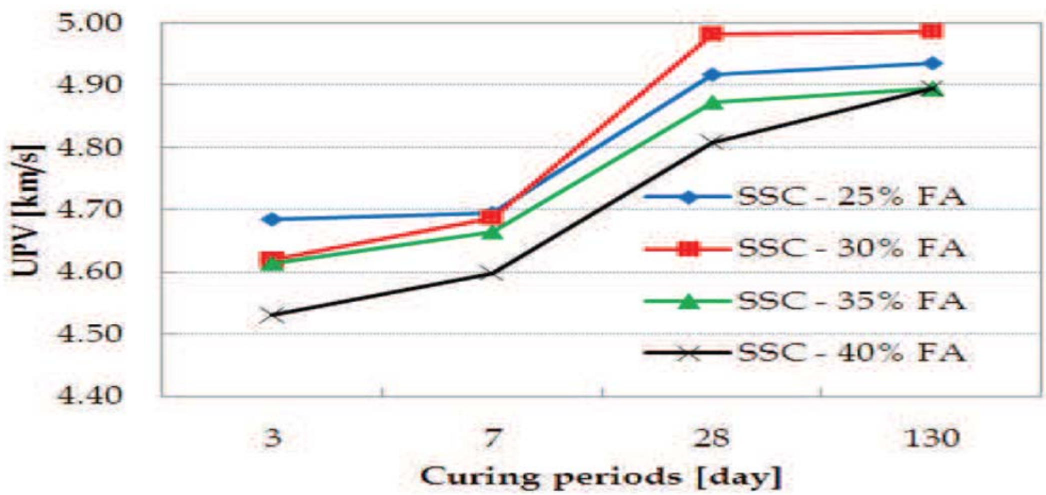
Fig. 2-1: Effect of w/c ratio on UPV (Ye et al., 2004)

2.3.3 Admixtures

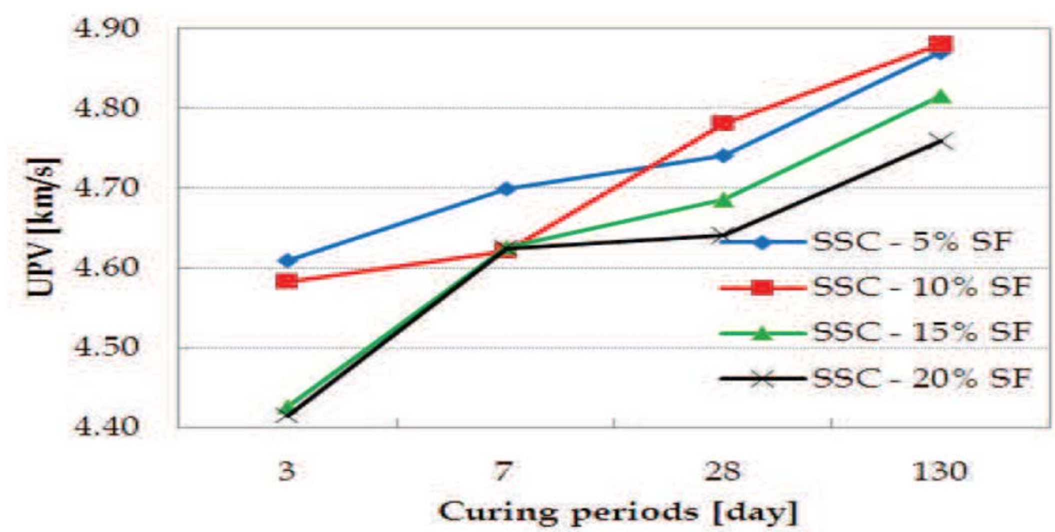
Admixtures, such as fly ash (FA) and silica fume (SF), are important ingredients of concrete. Silica fume is a highly effective pozzolanic material that fills the void spaces and can improve the density of concrete by pozzolanic reaction. Silica fumes have a capacity to fill micro-voids, creating a good bondage between paste and aggregate as well as reducing permeability. Fly ash (FA), on the other hand, has a capacity to fill microscopic voids between cement particles in self-consolidated concrete (SCC).

Ulucan, Türk, and Karata (2008) investigated the effect of silica fume (SF) and fly ash (FA) as mineral admixtures replacing Portland cement (PC) in self-compacting concrete (SCC). They found that the UPV values decreased with increasing FA replacement of PC in SCCs at 3 and 7 days; SCC containing 30% FA had the highest

UPV values at 28 and 130 days of curing period as shown in Fig. 2-2 a and b (Panzera, Christoforo, Cota, Borges, & Bowen, 1972).



(a)



(b)

Fig. 2-2: UPV result for self-compacted concrete (SCC) with (a) fly ash (FA) and (b) silica fume (SF) for different curing periods (from Panzera et al., 1972).

2.3.4 Age of Concrete

It is clear that the concrete matrix gets stronger with the curing period/age. The reason behind is due to the decrease in void spaces or the increase in the gel/space ratio that take place with paste hydration (Panzera et al., 1972). Since the pulse velocity through voids is less than that of solids and liquids, the greater the gel/space ratio (which increases with time), the lower the volume of pores and the greater the velocity of pulse propagated through the concrete (Ikpong, 1993). In addition, Jones (1954) reported that pulse velocity increases very rapidly at an early age and gets flatten later.

2.3.5 Volume of Steel Fibers (V_f) %

The addition of steel fibers to a plain concrete matrix is normally expected to increase its density due to its higher specific gravity, 7.84 (Journal of Engineering and Development, 2006). From wave propagation theory, the higher the material density, the higher the velocity of wave in it. Therefore, for SFRC of higher density, the UPV value is also expected to be higher. However, studies by Al-Owaisy (2006) showed that the UPV is much less enhanced or even decreased for higher volumes of steel fibers (Fig. 2-6). The reason is the development of voids and non-homogeneity in SFRC, which highly retarded the UPV (Journal of Engineering and Development, 2006). This situation is aggravated for steel fiber reinforced self-compacted concrete (SFR-SCC).

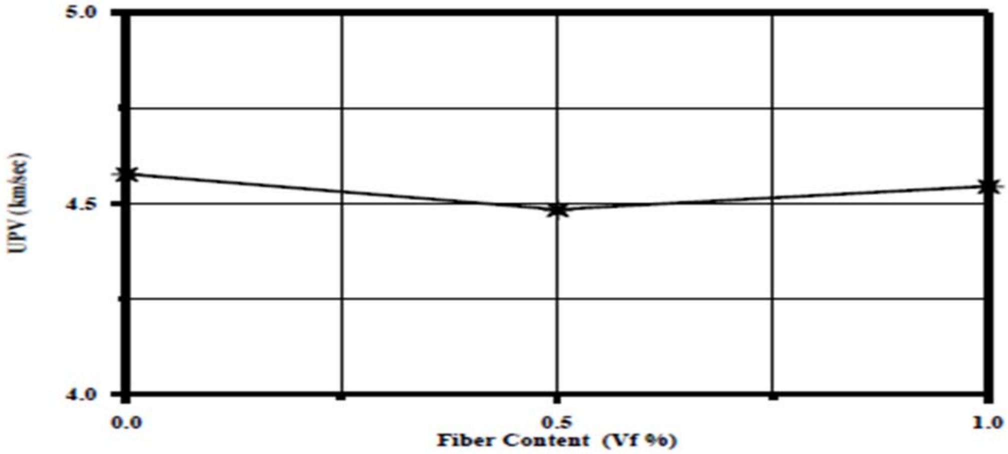


Fig. 2-3: Effect of fiber Volume on ultrasonic pulse velocity (From Al-Owaisy, 2006).

2.3.6 Other Factors

Other factors such as surface roughness, temperature, moisture condition, variable pressure on the transducers, presence of rebars, and porosity will affect UPV test result. Among these factors, surface roughness and porosity did affect the UPV reading significantly (Malhotra & Carino, 2004). These authors also reported that the UPV result was affected by large variations in temperature ($\geq 30^o$). According to the result, the UPV decreased with increasing temperature, porosity, and air-pockets between the transducer-sample interfaces and increased with the moisture content.

2.4 Applications of UPV

So far, the ultrasonic pulse velocity method has been applied in various applications, such as concrete quality control, defect identification, homogeneity test, and strength estimation (Woods & McLaughlin, 1959).

2.4.1 Concrete Homogeneity Test

Concretes can have deficiencies at early stages or can be deteriorated for several reasons through time. Concrete deficiencies at early age may arise from lack of proper mixing, poor mix design, insufficient water/cement (w/c) ratio, poor curing, and other environmental factors. On the other hand, concrete may be deteriorated with time due to chemical, mechanical and other service factors. Therefore, in order to identify and characterize the level of damage, UPV is of prime interest to professionals.

The ultrasonic pulse velocity method is suitable for the study of homogeneity of concrete, and therefore, for the relative assessment of the quality of concrete. Heterogeneity is defined as the existence of interior cracking, deteriorations, honeycombing, and variations of material compositions (ACI 544.1R, 1996). Therefore, by taking repeated measurements on different spots on the same sample and looking the ultrasonic pulse velocity variations, it is possible to identify the presence of heterogeneities inside the test materials. Heterogeneities in a concrete member will cause variations in the UPV (Kaplan, 1959). For example, the diffraction of a wave pulse around an internal air voids or cracks will cause an increase in the time of wave propagation for the assumed straight path (ACI 544.1R, 1996). Thus, the apparent pulse velocity will decrease accordingly.

Many existing structures were investigated using UPV method. Among these, the one that reported by Parker (1953) on the Hydro-Electric Power Commission of Ontario, Canada was very impressive. The survey was done on an existing dam built in 1914. A total of 50,000 readings were taken, most of them with 300-mm spacing. The pulse velocities measured on the structure ranged from below 1525 to over 5185 m/s, and these values were used, with success, to determine areas of advanced deterioration.

2.4.2 Estimation of Concrete Strength

The pulse velocity method may provide a means of estimating the strength of both in situ and precast concrete although there is no physical relation between the strength and velocity (Malhotra & Carino, 2004). Therefore, UPV can be used to estimate compressive strength as long as a calibration curve exists for each assessed materials (Madandoust, Ghavidel, & Nariman-zadeh, 2010). The relationship between strength and pulse velocity is not unique, and is affected by many factors, such as aggregate size, type, and content, cement type and content, water–cement ratio, and moisture content (Kaplan 1959, Anderson & Seals 1981). RILEM (1972), the British Standard (1986), and ACI 228.1R (1995) provided a standard practice to develop the relationship between UPV and compressive strength, which can be used to estimate in-situ strength. Different empirical relationships between concrete strength and UPV have been suggested by different researchers as follows:

$S = 8.4 * 10\text{-}9(Vp * 103)^{2.5921}$…………. (Nashn't et al., 2005)

$S = 1.19\exp(0.715Vp)$………………… (Kheder, 1999)

where S = concrete compressive strength (MPa) and

V_p = pulse velocity (m/s).

2.4.3 Estimation of Cement Hydration

The pulse velocity method has a real advantage of performing a continuous test and estimating the setting time of concrete without damaging the specimen. Whitehurst (1951) performed extensive research on 102 mm x 102 mm x 406 mm concrete prisms with zero slumps, using pulse velocity method; he reported that the UPV increased at rapid rate in the early stages, then the rate changed suddenly and continued at a slower rate. Thus, the inflection point is taken as the time of setting for the specified cement.

2.4.4 Estimation of Dynamic Modulus of Elasticity (E_d)

The velocity of compressional wave passing through an elastic medium is uniquely defined by the elastic constant and the density of the medium by the wave propagation theory (Malhotra & Carino, 2004). For homogeneous and elastic materials, UPV can be related to the density (ρ) and poison's ratio (v) of the material, as follows (Popovics, 2007):

Wave Velocity:

$$v_P = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}}$$

Governing Parameters

Young's Modulus E

Poisson's Ratio v

Density ρ

Eq. (1)

Whitehurst (1966) reported that it is possible to find the modulus of elasticity of the material using the UPV method if the density and Poisson's ratio are known. However, estimating the dynamic modulus of elasticity in concrete from ultrasonic pulse velocity measurements is not normally recommended for two reasons:

(1) The error resulting from inaccurate estimation of Poisson's ratio

(2) Equation 1 is appropriate for homogeneous materials only, leaving the validity for inhomogeneous materials, such as concrete, in doubt (Philleo, 1955).

Usually, the dynamic modulus of elasticity estimated from pulse velocity measurements is higher than that obtained from vibration measurements, even when the value of poison's ratio is known (Philleo, 1955).

CHAPTER 3

METHODOLOGY

ULTRASONIC PULSE VELOCITY (UPV) TEST

3.1 Background Information

Existing structures undergo severe internal deterioration that is unidentified with visual inspection, and causes fatal disasters. To avoid this, identifying flaws and performing pre-mitigation measures, either maintenance or demolition, are becoming key issues. Hence, the need arises for flaw detection and evaluation of structural concrete integrity in-service as well as newly casted concrete. Non-destructive ultrasonic pulse velocity concrete characterization is becoming the best alternative for this purpose. Unlike destructive test methods, non-destructive test methods require a relatively shorter time and lower cost (Warnemuende, 2006).

3.2 Ultrasonic Pulse Velocity (UPV) Test

The direct-contact through-transmission UPV test method was employed in this experiment. Based on ASTM C597-09 “Standard Test Method for Pulse Velocity through Concrete,” this method is based on the wave generated by an electro-mechanical transducer placed on the surface of the test specimen. The pulse velocity, V, of the stress waves can be related to the elastic property and density of the specimen, according to Equation 1 (ACI 544.1R, 1996). The ultrasonic pulse velocity test can be performed in different ways, such as through-transmission, pulse-echo, shear and surface waves. However, this experiment is based on the through-transmission method.

Through-transmission can be further differentiated as contact or non-contact, based on whether the transducers are in contact with the specimen or not. Non-contact transducers use water/air coupling as a transition medium. Contact transducers on the other hand, are placed directly in contact with the test specimen with the aid of a gel or grease to ensure perfect contact between the transducers and the test specimen faces. It can also sub-divide as direct, semi-direct, or indirect, based on the transducers' arrangement, as shown by Fig. 3-1. With through-transmission, the operator is more concerned with the transit time of the wave as well as the energy loss due to attenuation and wave scattering on flaws and medium change.

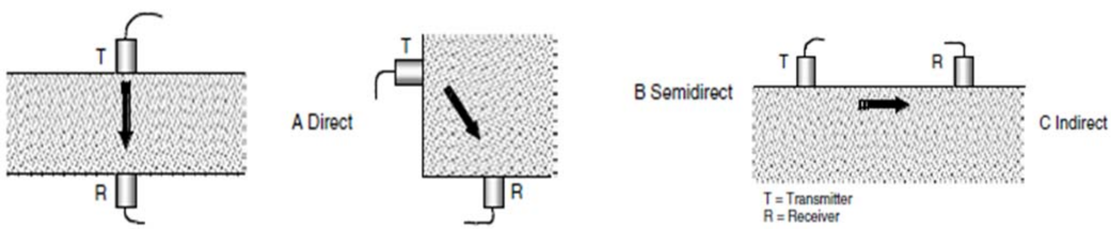


Fig. 3-1: Arrangements of UPV transducers (Center, 2009).

This test method can be applied to assess the uniformity and relative quality of concrete in order to indicate the presence of voids and cracks. It also can be used to estimate the progress of cracks and other deterioration, in the long run, by doing repeated tests on the same spot. As the name 'ultrasonic' implies, it is a wave-based method with a frequency range between 20 kHz (i.e., the human audibility limit) and 100 kHz (Center, 2009).

Though the method is simple, the accuracy of the result greatly depends on various factors such as the ability of the operator to interpret the result, surface roughness, alignment of the two transducers, temperature and moisture content. Starting from the instrument set onward, the operator must be alert to any unusual phenomena in order to get more precise result. Also, understanding the various parameters that can affect the pulse velocity reading (Sec. 2.5.2) is a key concern for this problem.

The test begins when an ultrasonic pulse is generated and transmitted for an electro-acoustic transducer, placed in contact with the surface of the concrete. After passing through the concrete, the vibrations are received and converted by the electro-acoustic transducer placed on the opposite face. The travel time (μs) and energy loss (dB) are displayed on the digital screen. In order to perform the test, a coupling agent, such as gel, should be applied between the transducers face and specimens' surface to ensure that there is no air pocket between them. The oscilloscope on the digital screen is very sensitive to air pockets created by the pores and any roughness on the test surface, which may mislead the operator to assume there are internal imperfections. It is also equally important to align the two transducers so that the measured distance and the actual path length for the wave have a perfect match.

The results obtained using this test method are not to be considered as a means of measuring strength nor as an adequate test for establishing compliance of the modulus of elasticity of field concrete with that assumed in the design (ASTM C597-09). However, when circumstances permit, a very reasonable velocity-strength or velocity-modulus relationship may be established by determining the pulse velocity and compressive strength (modulus of elasticity) on a number of concrete samples based on the ACI 228.1R-95 procedure.

CHAPTER 4

MATERIALS AND EXPERIMENTAL PROGRAM

This section describes the experimental program of this study to investigate the effects of deformed steel fibers on the UPV evaluation of self-compacted (SC) steel-fiber-reinforced (SFR) concrete with various admixtures.

4.1 Constituent Materials

4.1.1 Steel Fibers

ASTM A 820-90 Type II deformed Cut Sheet Carbon Steel Fibers were used, having an equivalent diameter of 0.023 in (0.584 mm) and a length of 0.75 in (19.05 mm). The specific gravity of carbon steel fiber was 7.85, which is much higher than any of the constituent materials. The steel fibers had rectangular cross-sections of 0.406 x 0.838 x 19.05 mm (0.016 x 0.033 x 0.75 in). The tensile strength of the steel fibers ranged between 379 to 763 MPa. These fibers were selected to get a strong bondage between the concrete matrix and steel fibers; which in turn would improve the ductility of concrete.

4.1.2 Aggregates

Coarse and fine aggregates were obtained from a local quarry in the Las Vegas, Nevada area. Two different sizes of coarse aggregate with nominal sizes of 9.53 mm (3/8’’) and 6.35 mm (#4 sieve) were used in this experiment. The type of aggregate used was crushed limestone. Natural sand as fine aggregates was also added to the mix. Table 4-1 demonstrates the details of fine and coarse aggregates.

Table 4-1: Properties of Aggregates (Ladkany and Berhe, 2013a)

Parameter	Type	Size (in)	Amount lb/ft3	Sp. Gravity	Absorption (%)	Fineness Modulus	ASTM Standard
Coarse agg.	Limestone	3/8" & #4	22.8 & 22.4	2.777	0.6	N/A	ASTM C 128-07a
Fine agg.	Natural sand	N/A	57.6	2.785	0.64	3.03	ASTM C 128-07a

4.1.3 Cement

ASTM C 150 Type V ordinary Portland cement (OPC), 404 kg/m3 (25 lb/ft^3), was used to prepare the test specimens. Type V OPC has a high sulphate resistance and lower setting time than Type I OPC. Cement is a binder material used to strengthen the concrete. It actively reacts with water (hydration process) to produce an inert and strong concrete cast.

4.1.4 Water

The amount and chemical composition of water plays an important role in controlling the mechanical properties of concrete. Adding excess water will reduce the strength of concrete, wash binder materials, and leave pores and voids after hardening due to evaporation of excess water. On the other hand, too little water also can cause for poor strength and workability in concrete. Similarly, the chemical compositions of water play a significant role in the cement hydration process, which controls the concrete quality. Therefore, considering all these factors, a tap water of 10.224 lb/ft^3 was added in this experiment.

4.1.5 Fly Ash (FA)

Fly ash is an important admixture to improve the workability and reduce the demand of cement or fine fillers in steel fiber reinforced self-compacted concrete (SFR-SCC). It has a great role in creating a sufficient amount of cement paste in SFR-SCC and improves the mechanical properties by filling the micro-pores in it (Khurana and Saccone, 2001**)**. Class F fly ash (FA) with weight fraction of 10.7 lb/ft^3, Blaine fineness and specific gravity of 5.23 x 10^3 cm^2/g and 2.1 respectively, were used in this experiment. The presence of fly ash leads to an increase in the amount of tri-calcium aluminates present and also an increase in the content of calcium silica hydrate formed in pozzolanic reactions. Consequently, there are less free chlorides available to initiate corrosion (Dinakar, Babu, & Santhanam, 2008).

4.1.6 Silica Fume (SF)

Silica fume is the small-sized particle approximately 100 to 150 times smaller than Portland cement particles, and has a high surface area and high amount of silicon dioxide (Khurana and Saccone, 2001*)*. This submicron size of silica fume allows it to fill open voids in the cement as sand does in coarse aggregate. However, the higher surface area of silica fume demands much water to wet it. This, in turn, increases the w/c and hence decreases the concrete strength (Kaplan, 1959). Therefore, to solve this problem, the use of superplasticizers known as High Range Water Reducing Agents (HRWRAs) is important.

A 1.9 lb/ft^3 of silica fume was used in this experiment. This silica fume was selected for its chemical and physical benefits. The chemical reaction known as the "Pozzolanic" reaction takes place when Portland cement is hydrated (mixed with water), producing many compounds, including calcium silicate hydrate (CSH) and calcium hydroxide $Ca(OH)_2$. CSH, sometimes called the gel, is the source of strength in concrete. Therefore, when silica fume is added to fresh concrete, it reacts with $Ca(OH)_2$ to produce additional CSH; this enhances concrete strength (Ulucan et al., 2008).

4.1.7 Superplasticizer (SP)

Superplasticizers play an important role to improve concrete workability and strength in SFR-SCC with fly ash and silica fume (Ulucan et al., 2008). ADVA 140 high range water reducer (HRWR) was selected for this experiment. A constant amount of 0.392 lb/ft^3 HRWR was added to the cylindrical samples of variable fiber contents. The HRWR content varies with steel fiber content for the beam samples (Table 4-2).

4.2 Mix Proportions

The mix proportion was designed so as to improve the common drawback (i.e., brittleness) of concrete and other mechanical properties. It consists of coarse aggregate, fine aggregate (sand), cement, fly ash, silica fume, water, superplasticizer, and deformed steel fibers as shown in Tables 4-2 & 4-3.

Except for the volume percentage (V_f) of steel fibers and superplasticizers, all the other constituent materials were kept constant for the beam samples. The amounts of superplasticizers were selected to provide the best workable concrete matrix for the respective percentages of steel fibers by trials and errors. The cylindrical samples, on the other hand, have all the constituent materials constant except the volume of steel fibers. However, unlike the beam samples, the amount of superplasticizer was kept constant for the cylindrical samples at 0.392 lb/ft3; which was best for 0% fiber concrete workability, and adapted for the rest just for the sake of minimizing the number of variables and to realize the sole effect of steel fiber volumes in SFRC.

Table 4-2: Mix Proportions for Beam Samples (Berhe and Ladkany, 2013a)

Mix Component	Unit	Mix Category				
		0 % Fiber	1 % Fiber	2 % Fiber	3 % Fiber	4 % Fiber
3/8" Coarse Aggregate	lb/ft^3	22.8	22.8	22.8	22.8	22.8
#4 (4.75 mm) Coarse Agg.	lb/ft^3	22.4	22.4	22.4	22.4	22.4
Fine Aggregate (sand)	lb/ft^3	57.6	57.6	57.6	57.6	57.6
Water	lb/ft^3	10.224	10.224	10.224	10.224	10.224
Cement Type V	lb/ft^3	25	25	25	25	25
Silica Fume	lb/ft^3	1.9	1.9	1.9	1.9	1.9
Fly Ash (Class F)	lb/ft^3	10.7	10.7	10.7	10.7	10.7
Water to Cement Ratio		0.41	0.41	0.41	0.41	0.41
HRWR (Superplasticizer)	lb/ft^3	0.392	0.372	0.416	0.432	0.472
Steel Fibers by Volume	%	0	1	2	3	4
" " " Weight	lb/ft^3	0	1.25	2.5	3.75	5

Table 4-3: Mix Proportions for Cylindrical Samples (Berhe and Ladkany, 2013b)

Mix Component	Unit	Mix Category		
		0 % Fiber	1 % Fiber	2 % Fiber
3/8" (9.53 mm) Coarse Aggregate	lb/ft^3	22.8	22.8	22.8
#4 (6.35 mm) Coarse Aggregate	lb/ft^3	22.4	22.4	22.4
Fine Aggregate (sand)	lb/ft^3	57.6	57.6	57.6
Water	lb/ft^3	10.224	10.224	10.224
Cement Type V	lb/ft^3	25	25	25
Silica Fume	lb/ft^3	1.9	1.9	1.9
Fly Ash	lb/ft^3	10.7	10.7	10.7
Water to Cement Ratio		0.41	0.41	0.41
HRWR superplasticizer	lb/ft^3	0.392	0.392	0.392
Steel Fibers by Volume	%	0	1	2
" " " Weight	lb/ft^3	0	1.25	2.5

4.3 Specimens Preparation

A total of 18 beam and 5 cylindrical samples were prepared for this experiment. The main experimental program is based on the beam samples since relatively representative samples are available. However, since the beam samples were aged (more than a year), it was not possible to see the curing period effect. Therefore, the cylindrical samples were prepared to investigate the curing period effect on UPV. The 18 beam samples were categorized in to 5 groups: four of them had 4 members with the steel fibers volumes of 0%, 1%, 2%, and 3%, respectively; the fifth had 2 members with 4% fiber volumes. Similarly, the cylindrical samples had 3 groups of 1 (0%), 2 (1%), and 2 (2%) steel fibers, respectively. The dimensions of all beam and cylindrical samples were 4 in x 4 in x 14 in and 4 in ϕ x 8 in, respectively. Except for the amount of superplasticizers at 1% and 2% fibers, all the constituent materials were the same for both the cylindrical and beam samples. Fig. 4-1 and 4-2 illustrate the beam and cylindrical samples.

Dry mixing of coarse aggregate, fine aggregate, cement, fly ash, silica fume, and steel fibers were performed for about 1-2 min using a mechanical mixer. Then, about 80 % of water was added and mixed thoroughly for the specified time.

Finally, the remaining portion of water and HRWR were added at the end before discharging the mix. The concrete matrix was poured into the mold and allowed to set without any vibrational effort (i.e. Self-Compacted Concrete, SCC). The samples were prepared based on ASTM C 192.

Fig. 4-1: Aged beam samples

Fig. 4-2: Cylindrical samples

4.4 Experimental Program

4.4.1 Description of Variables

In this experiment program the main variables are volume of steel fiber, sample saturation, curing periods, fiber orientations, and porosity. The effects of fiber volumes ranging from 0-4% on ultrasonic pulse velocity were investigated. In addition, the variation of UPV through the saturated and air dried samples also assessed. The curing periods effects on UPV were addressed for the 7, 28, and 90 days. The steel fiber orientations effects on UPV were also performed.

4.4.2 Instrument and Setup

Ultran WN 75-1-X NCA 1000 Direct Contact ZERO DEGREE LONGITUDINAL WAVE transducer, nominally 1MHz and 19 mm active diameter with side BNC, was utilized in this experiment. A digital imaging device to display the test result and oscillation also was utilized. A digital caliper was used to measure the dimension of the test specimen, and regular gel was used to fill gaps between test surface and transducers faces. Figure 4-3 depicts the apparatus used in this experiment.

The NCA 1000 Transducer Setup was as follows:

- Serial Number 210,841 & 210,842
- Mode of Testing: Contact Direct Transmission
- Signal Type: CHIRP Signal
- CHIRP Parameters:
    - Frequency: 950 kHz
    - Bandwidth: 900 kHz

- Chirp duration: 50 µs
- Alt sequence: 10 µs
- Amplitude: 75 %
- Chirp step-A: 45 %
- Chirp step-B: 45%

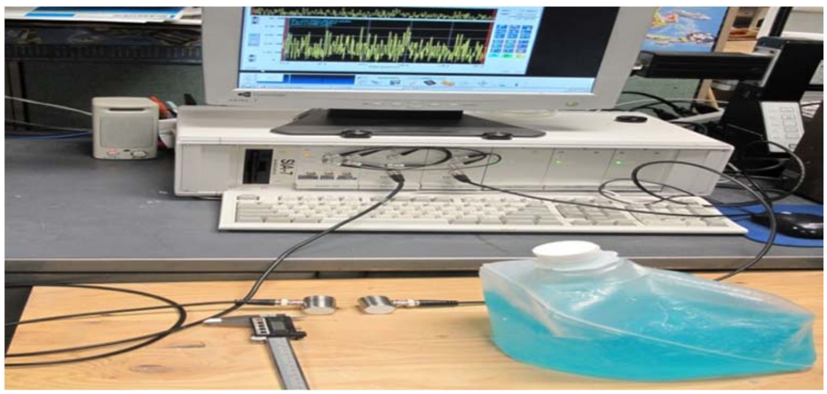
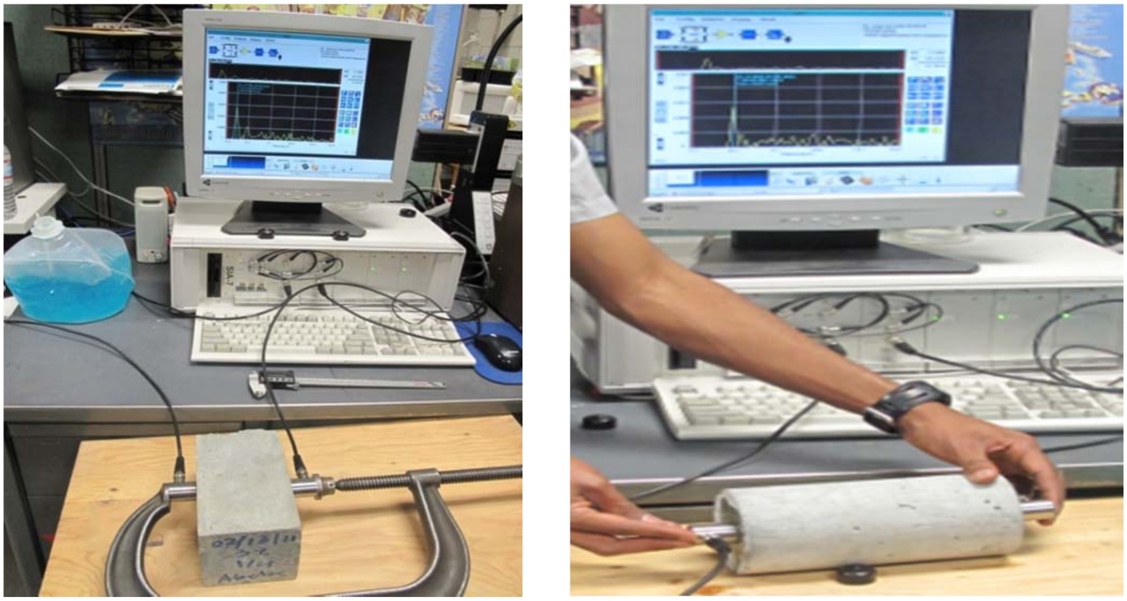


Fig. 4-3: Test instruments used in this experiment.

4.4.3 Test Procedures

Once the instrument was set up, the next critical step was testing. This was critical because the highest percentage of errors can occur in this part of the experiment. Before starting the experiment, the test specimen was placed on a level and stable surface; a digital caliper was used to measure the length of specimen along the direction of the wave. A gel was applied on both faces of the specimen where the transducers were to be placed so that the two faces of the transducers and test specimen had full contact.

There should not be any uneven surface and/or air pockets between transducers and specimen contact faces. Also, the two transducers needed to be aligned so that the measured dimensions and assumed wave travel path were the same. The same amount of pressure was applied on the two transducers to avoid instability of amplitude of the wave, as shown in Figs. 4-4 a and b.



(a) (b)

Fig. 4-4: Ultrasonic Pulse Velocity (UPV) testing.

Finally, the test results were displayed on the digital screen, including the time of flight (T of F) in micro-seconds (μs) and Integrated Response (IR) in deci-bels (dB). For a precise measurement, the oscilloscope had the first peak value, and decayed with time, as shown in Fig. 4-5. Either due to incorrect measurements or the presence of imperfections in the test specimen, the oscillation sometimes had more than one peak and an unstable reading, as shown in Fig. 4-6.

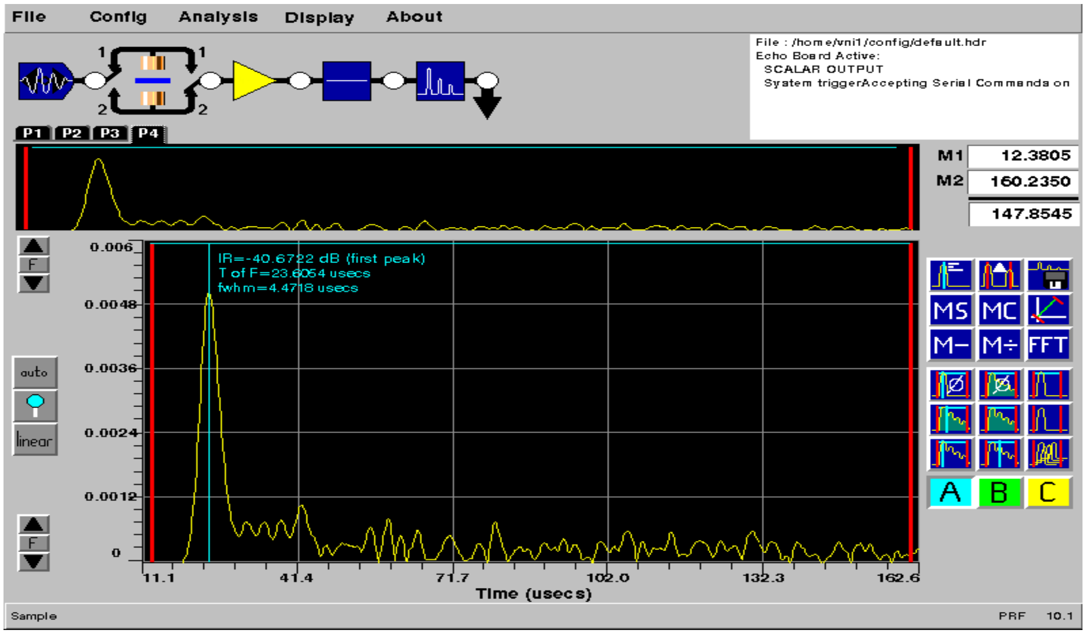


Fig. 4-5: Wave propagation for proper measurements.

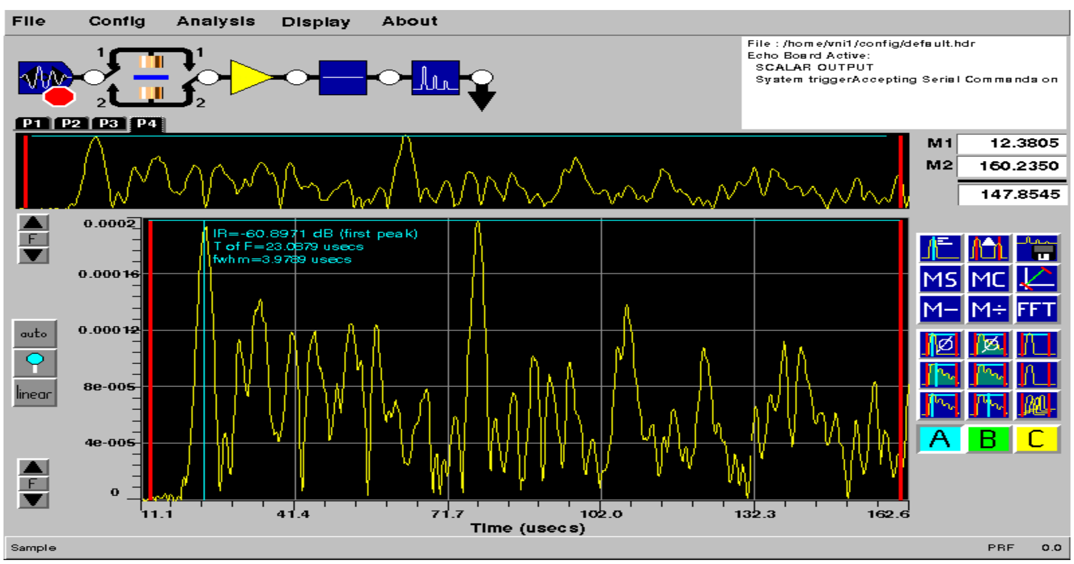


Fig. 4-6: Wave propagation for defective measurements.

CHAPTER 5

RESULT AND DISCUSSION

5.1 Cylindrical Samples

5.1.1 General

Five cylindrical samples were prepared for this study. The dimensions of all the samples were 4 in x 8 in. These samples were categorized in to three groups according to their percentage of steel fibers as 1 (0%), 2 (1%), and 2(2%) fibers by volume. Except for the fiber content, all the other constituent materials are kept constant for all samples. The samples were self-compacted to avoid materials segregation and bleeding. From visual observation, the fibers in the cylindrical samples had relatively fair distribution and orientation compared with the beam sections in which the fibers had fair distribution but with a bias on the fibers' orientation along the longitudinal axis in the horizontal plane. In addition to the relatively higher height of the cylindrical mold, the weight of the mix had a contribution on the density of the sample. The test was performed in the longitudinal direction, as shown in Fig. 5-1.

Fig. 5-1: Longitudinal measurement for cylindrical samples.

5.1.2 Relationship between Volumes of Steel Fibers and Voids

Normally, the addition of steel fibers greatly contributes to the development of voids. Since the presence of fibers interrupt free movement of the mix, more void spaces are created. To mitigate this problem, a constant amount of 0.392 lb/ft^3 High Range Water Reducer (HRWR) superplasticizers were added to all the samples. However, this amount was best designed for a 0% steel fiber mix. For the sake of minimizing the number of variables, the superplasticizer was kept constant and the fiber volume was allowed to vary. Therefore, due to the best match superplasticizer, the 0% fiber mix had the least voids, whereas the voids increased with the fiber volumes for 1% and 2% fiber mixes, respectively. Analytical void calculations were performed, using bulk density of the samples to compare with the test result; they showed a good agreement, as shown in Fig. 5-2.

Table 5.1: Summary Table for Cylindrical Samples

Volume of Steel Fibers (%)	Specimens' Age (Days)	Avg. UPV (m/s)	90th day Avg. Bulk Density (lb/ft^3)	Calculated % Void (Porosity)
0	7	4793.13	156.2	1.5
	28	5010.85		
	90	5071.61		
1	7	4724.88	157.4	10.6
	28	4770.62		
	90	4934.32		
2	7	4634	158.7	14
	28	4642.22		
	90	4782.1		

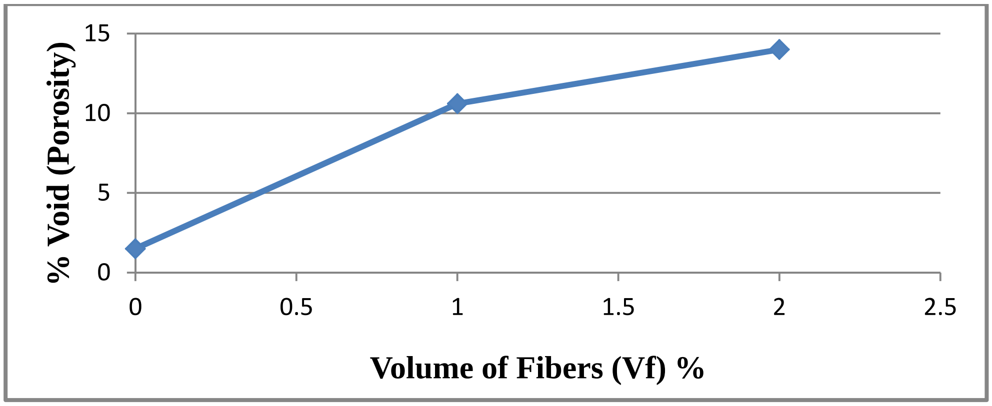


Fig. 5-2: Relationship between porosity and volume of fibers for the cylindrical samples.

5.1.3 Effects of Steel Fiber Volumes (V_f) % on UPV

Generally, the addition of certain amounts of steel fibers increases the UPV of the mix due to its high specific gravity, 7.85. Hence, it was expected that the 0% fiber sample would have less UPV than the 1% and 2% fiber samples. However, due to the cumulative effect of superplasticizer and no fiber interruption in the 0% fiber mix, the UPV was the highest in the 0% fiber sample and decreased for 1% and 2% fibers, respectively, as shown in Fig. 5-3.

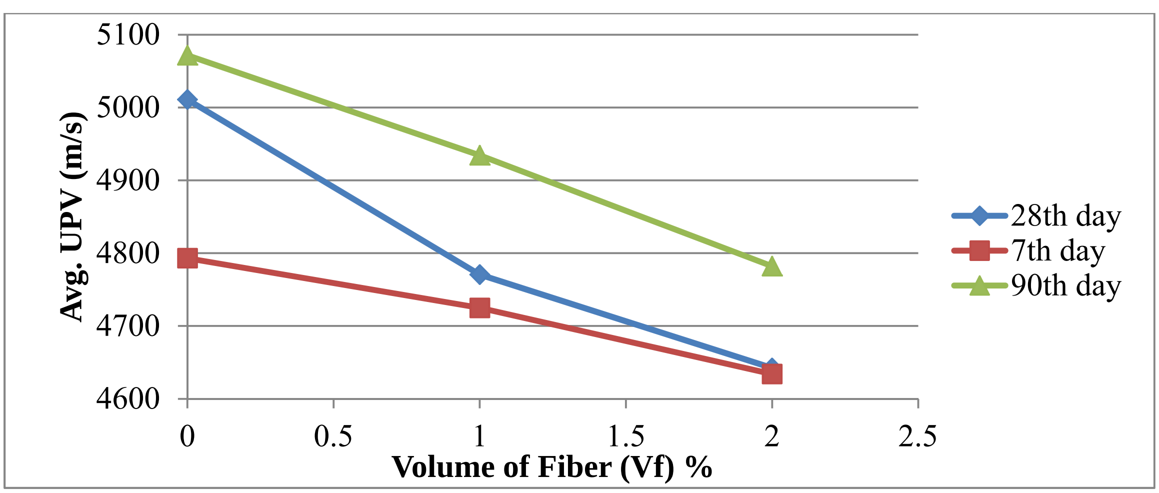


Fig. 5-3: Effect of the volume of steel fibers (V_f) % on UPV for cylindrical samples.

5.1.4 Relationship between UPV and Voids

The presence of voids and other heterogeneities greatly affected the UPV test result. The speed of wave propagation is dependent on the material's density and elastic property. The pulse wave travels faster through solid media than through liquid and gas. In addition, the pulse wave is highly sensitive for changes in the medium, whether by increasing or decreasing. For instance, as observed in this experiment, for an increase in 1μs (0.000001 sec) travel time of the wave due to voids, there was an average decrease of 172 m/s in the ultrasonic pulse velocity, keeping all other parameters constant. The graph in Fig. 5-4 for UPV and the analytically calculated voids (Appendix A) were in good agreement with this explanation.

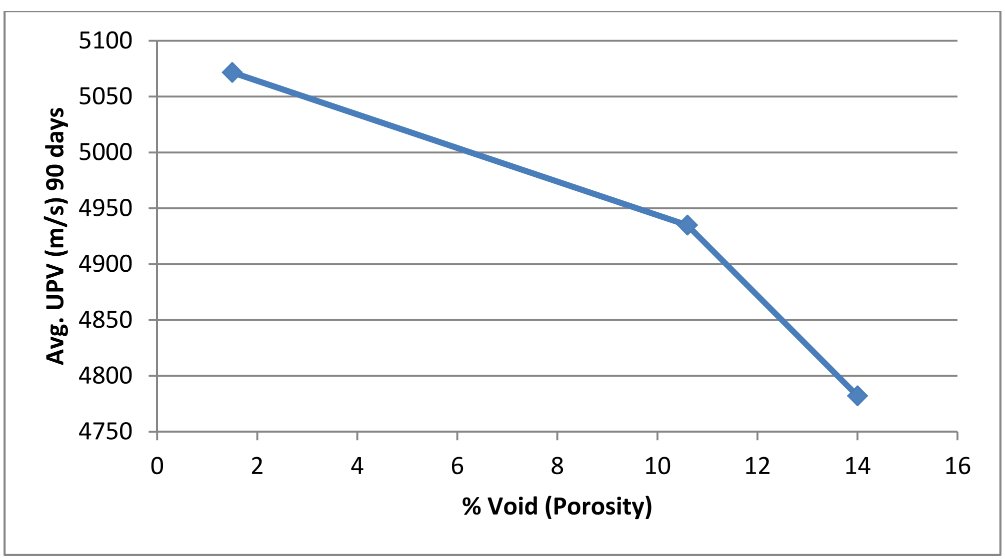


Fig. 5-4: Relationship between % voids (porosity) and UPV for the cylindrical samples.

5.1.5 Effect of Wet and Dry Conditions on UPV

The effect of saturation on UPV was also investigated in this experiment. The result showed that saturated samples had a higher pulse velocity than air dried samples of the same category (Fig. 5-5). As depicted in the graph, the moisture content did not have a significant effect on UPV for 0% fibers due to the least amount of voids that could be filled with water. However, the effect was more pronounced as the percentage volume of steel fibers increased. This happened because of the fact that the increase in fiber content increases the void space, as proved in this study Section 5.1.2, and hence more moisture was absorbed by the concrete. According to the wave theory (Center, 2009), the speed of the ultrasonic waves in solid > water > air. Therefore, the UPV in saturated medium is greater than that in a dry medium in the presence of pores/voids.

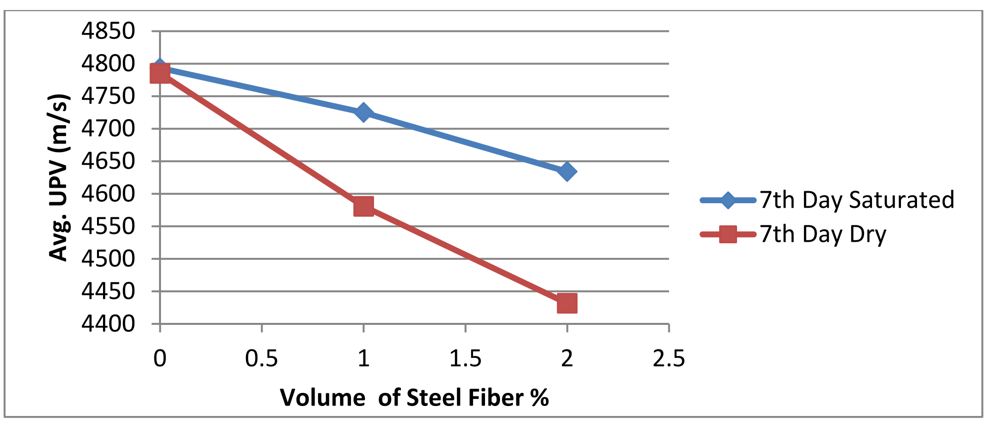


Fig. 5-5: Effect of moisture conditions on UPV for the same cylindrical specimens.

5.1.6 Effects of curing periods on UPV

The curing period has a great influence on the value of the UPV test result. The pulse velocity increased rapidly at an early period of the specimen for 0% steel fibers.

The reason was that most of the hydration process and gap filling were carried out within an early period of 28 days. During these periods, the concrete got its maximum strength and density, more or less. On the other hand, the presence of steel fibers and addition of insufficient superplasticizers in 1% and 2% fiber volumes, delayed/retarded the gap filling or consolidation time of concrete; hence, the UPV increased gradually, as shown in Fig. 5-6. Generally, for the proper mix design, the UPV increases rapidly at an early period and gets gradual increase/flatten afterward which is in good agreement with the result obtained by Whitehurst (1951). This is a good indication of the UPV can be used to estimate the setting time of concrete.

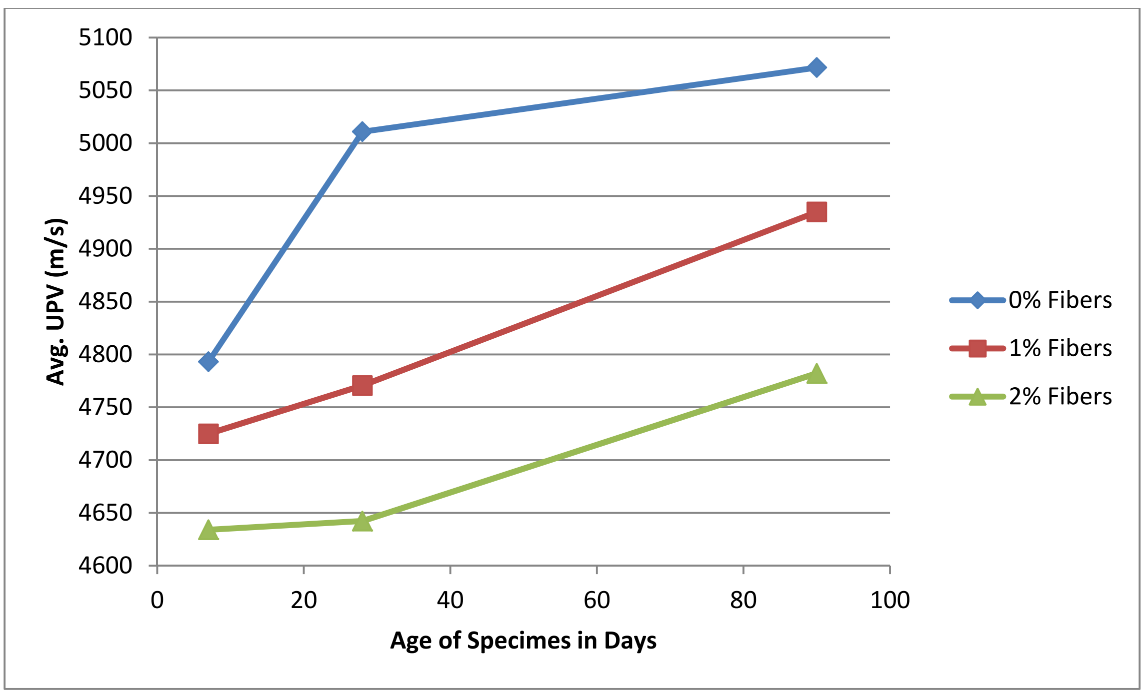


Fig. 5-6: Effect of curing period on UPV for different fiber volumes of cylindrical samples.

5.2 Beam Section Samples

5.2.1 General

A total of 18 beam section samples were prepared for this study. These 18 samples were categorized in to five groups based on their fiber content: 4 had 0% fiber, 4 had 1% fiber, 4 had 2% fiber, 4had 3%, and 2 had 4% fiber. All the samples were designed to have dimensions of 4 in x 4 in x 14 in, unlike the cylindrical samples, in which the amount of superplasticizers were kept constant.

The superplasticizers were allowed to vary with the percentage of steel fibers, as shown in Table 4-2. This means the best match superplasticizers were added to each category to get the best workable mix. Due to less height of the beam section mold, the effect of self-weight on the density was insignificant; hence, the beam samples had less density than the cylindrical samples.

The UPV measurement was performed along the width (side) (Fig. 5-7) for the general test, whereas for the fiber orientation effect, measurements were taken along all the three faces of the beam.

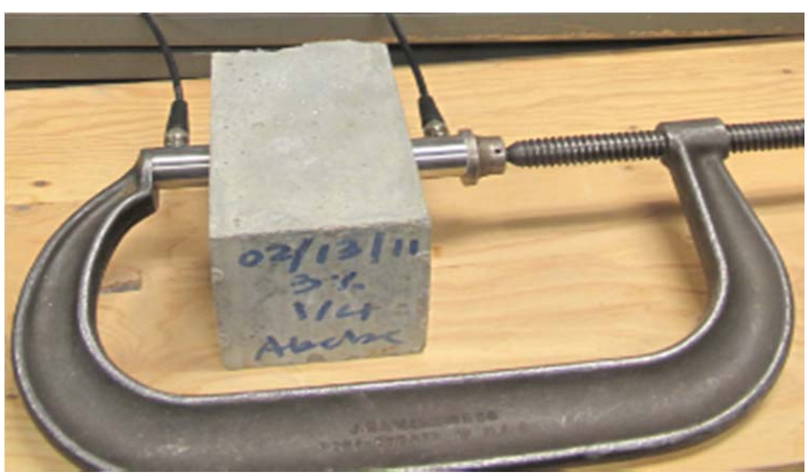


Fig. 5-7: UPV measurement along the sides for the beam samples.

5.2.2 Relationship between Steel Fiber Volumes (%) and Voids

As mentioned previously for the cylindrical samples, the presence of steel fibers greatly contributed to the development of voids. To mitigate this problem, the HRWR superplasticizers were allowed to vary with the volume percentage of steel fibers in order to get best workable mix for the beam samples. In fact, the test result proved that it was possible to minimize the amount of voids by adding the optimal amount of superplasticizers. However, for higher volume percentage of steel fibers ($V_f > 2\%$), the addition of superplasticizer was not helpful to avoid formation of voids, due to a significant interruption of steel fibers in the free movement of pastes. Therefore, the UPV and other concrete properties were observed to decrease beyond 2% steel fibers by volume (Fig. 5-8).

Normally, it is not uncommon to see a very small amount of increment in voids, like the lower portion of the blue line in Fig. 5-8, whenever 1-2% fibers are added to a plain concrete. This is because the addition of steel fibers always interrupts the free movement of the paste regardless of the presence of superplasticizer.

Table 5-2: Summary Table for Beam Section Samples

Parameters	Measured and Calculated Values				
Volume of Steel Fiber (%)	0	1	2	3	4
Avg. UPV (m/s)	4257.72	4339.61	4512.19	4481.58	4442.48
Calculated % Void (Porosity)	13.2	14	14.2	17	18.6
28th day Avg. Density (lb/ft3)	135.5	146	153.1	156.5	160.9

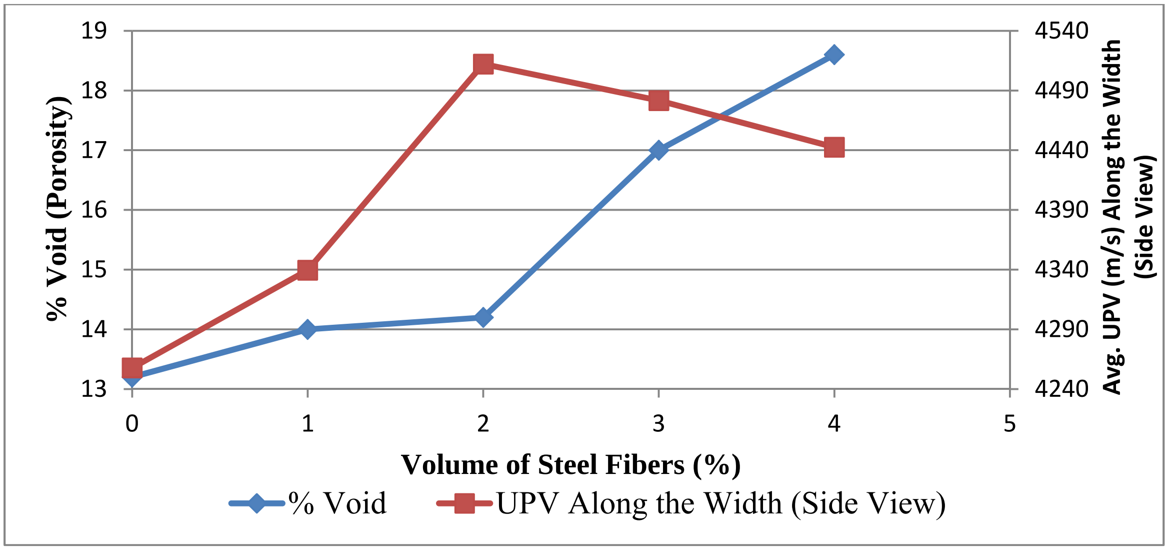


Fig. 5-8: Effect of steel fiber volumes and %voids on UPV for the beam samples.

5.2.3 Relationship between UPV and % Voids

The presence of voids retards the UPV test result. Contrary to this fact, the UPV is observed to increase regardless of a very small increment in voids for the range of 0-1% fiber volumes (Fig. 5-9). The reason is that even though the very small increment of voids tends to retard the UPV, the presence of steel fibers has greater influence on increasing the UPV due to its high wave propagating capacity. That means the rates of influence of voids and steel fibers on UPV are not the same (i.e., the latter is greater). Similarly, for the range of 1-2% of steel fibers, the change in voids is insignificant but the change in steel fiber volume is double. Therefore, the UPV increased rapidly due to the absence of voids effect. On the other hand, for a very significant increase in voids from 2-4% of fibers, the effect of voids on UPV is pronounced and dominates the positive effect of fibers on UPV. Hence, the UPV starts to decrease gradually.

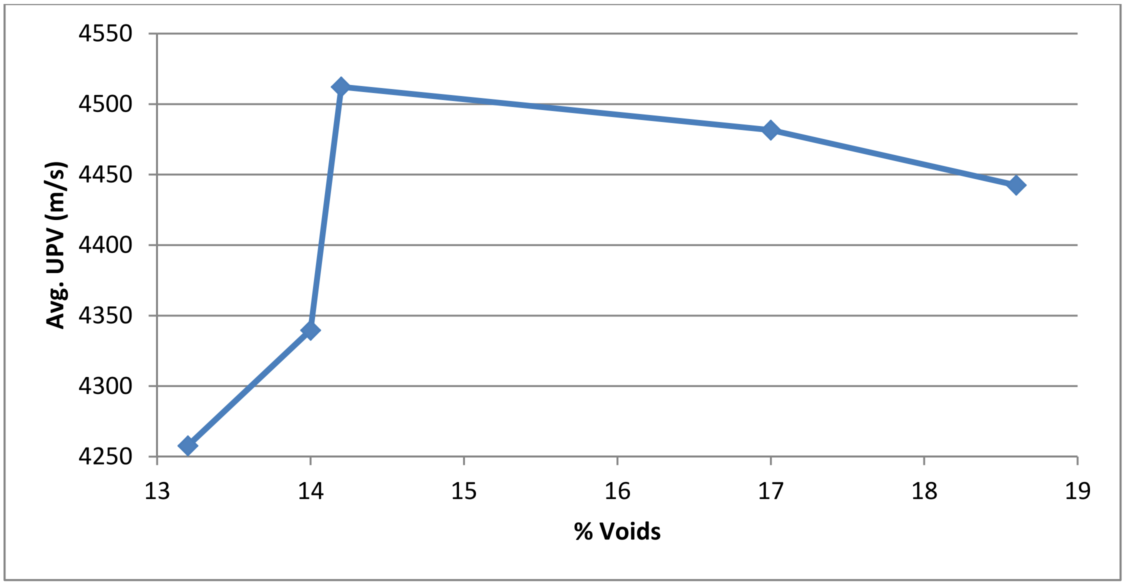


Fig. 5-9: Relationship between % voids and UPV for the beam samples.

5.2.4 Effect of Steel Fiber Volumes (%) on UPV

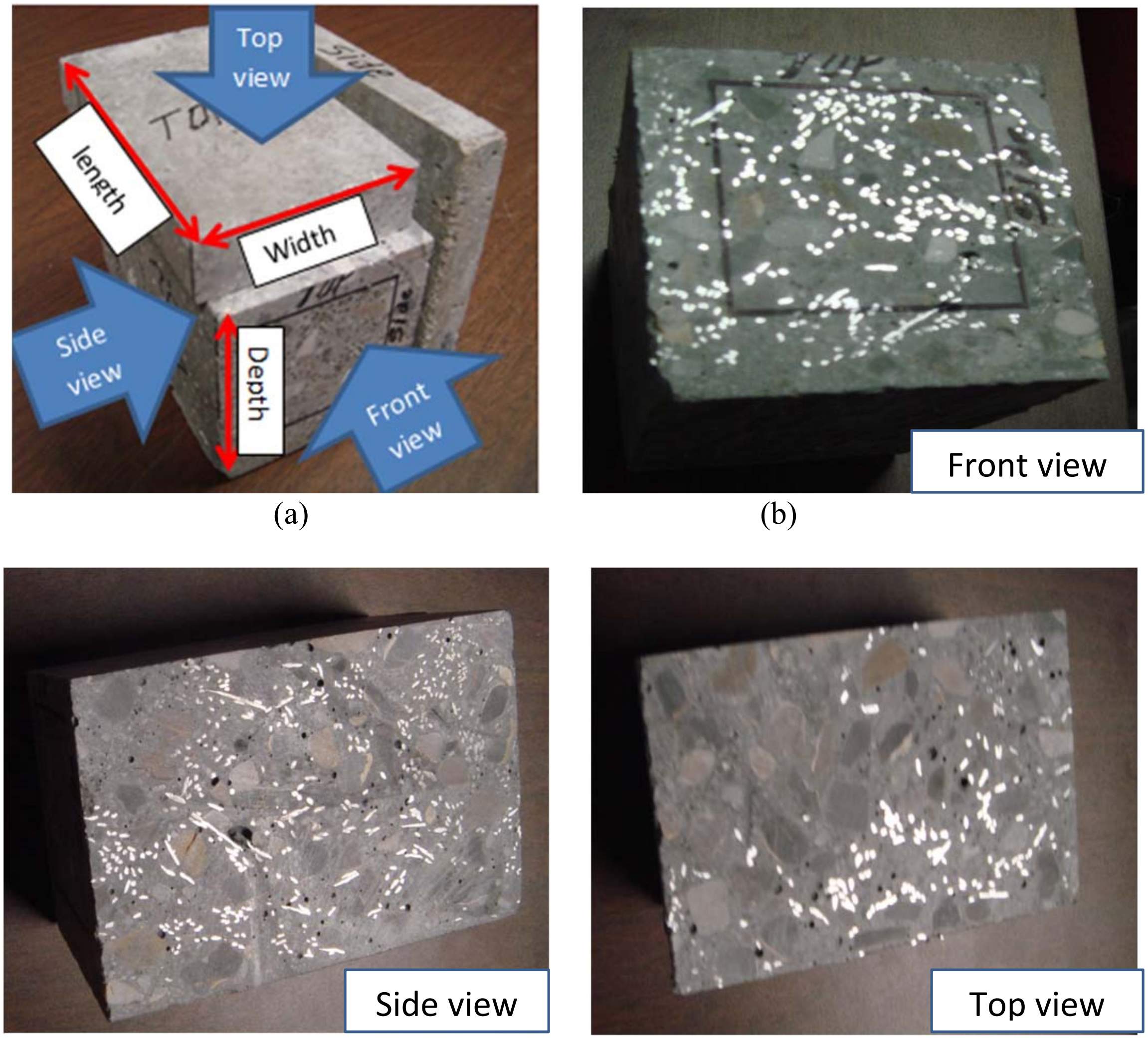
The presence of short, deformed, and randomly distributed steel fibers affected the UPV measurement both positively and negatively. For the beam sections, the addition of 2% steel fibers to a plain concrete increased the average pulse velocity by approximately 6% (Fig. 5-8). However, further addition of fibers did not improve either the UPV or other concrete properties. The reason is that since the test samples were self-consolidated samples, the addition of more fibers initiated the formation of voids by reducing the workability of the matrix. This, in-turn, decreased the speed of wave propagation through the sample and resulted in a lower UPV value. Though a properly match HRWR superplasticizer was added to the mix to improve its workability, the problem couldn't be solved and was even pronounced for higher fiber volume (4%). Therefore, for a steel-fiber-reinforced, self-compacted concrete, 2% by volume of steel fiber is an optimum amount to be added to improve the properties of concrete structures with a corresponding superplasticizer.

5.2.5 Effect of Fibers Orientations on UPV

Although the samples were self-consolidated, there is always a tendency for the aggregates and fibers to lie down along a horizontal plane with their longer dimensions due to the stability requirement. Figure 5-10 strengthens this assumption, since most of the fibers were oriented parallel to the longer side of the mold in a horizontal plane.

Fig. 5-10: Fiber orientations of a beam sample.

The orientation of the fibers indeed affected the UPV result. This study proved that for the same sample, the UPV was higher along the direction where more fibers were oriented. The approximate count per square inch concentrations of fiber orientation were 11.6 fibers/in^2, 32 fibers/in^2, and 50 fibers /in^2 on the top plane, side plane, and front plane, respectively (Fig. 5-11 b-d). Therefore, these variations of fiber concentrations resulted in different UPV values for the same sample along different directions, leaving the highest value along the length (front plane) and the lowest value along the depth (top plane) as shown by Fig. 5-12.



(a) (b)

(c) (d)

Fig. 5-11: Concentration of steel fibers in different planes: a) the original shape as if in the mold, b) front view, c) side view, and d) top view.

The UPV variation/increment along the depth and width was more or less uniform, and is most probably due to the aggregate orientations in the horizontal plane parallel to the width. Since most of the fibers were oriented/concentrated along the length (front plane), as shown above, their effect seemed to be very small on the UPV measurements, along the width and depth. If not, the gap between the two readings would be smaller at 0% fibers and would widen with increasing fiber content.

Unlike the depth and width, the orientation of aggregates had less influence on UPV along the length and the width since both of them had horizontal planes. Therefore, the variations between the UPV readings across front and side planes were mostly due to the fibers' orientation, since their UPV values had a small difference at 0% fiber and the variations increased as the fibers content increased.

On the other hand, the differences between the UPV readings along the length and the depth were cumulative effects of both fibers and aggregate orientation, since they had different pivots at 0% fiber and the difference increased with the fibers' volume. Therefore, the fibers and aggregate orientation made a significant difference on the UPV value. That is, the UPV increased in the direction of fiber and aggregate orientation.

Table 5-3: Summary of Average UPV Test Result along Different Direction on the Same Sample of Varying Fiber Content.

% Fibers	Values of UPV (m/s) along the			Average UPV (m/s)
	depth	width	length	
0%	4220.48	4251.04	4264.04	4245.19
1%	4297.77	4361.32	4412.18	4357.09
2%	4353.13	4434.41	4513.64	4433.72
3%	4267.94	4342.56	4420.07	4343.52
4%	4253.25	4301.31	4342.87	4299.14

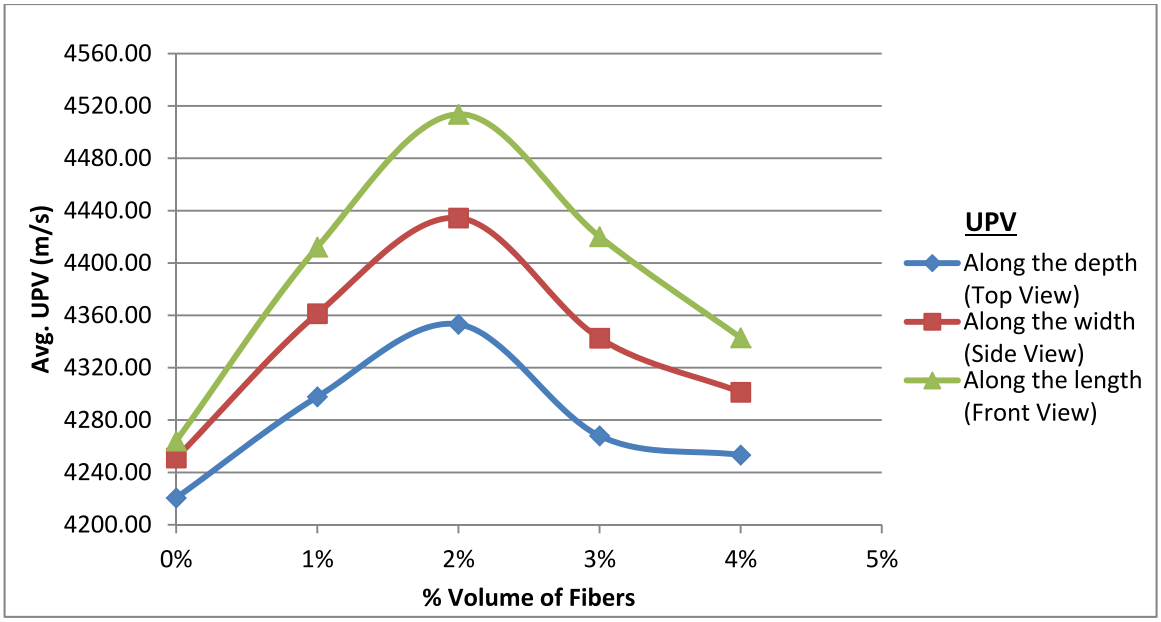


Fig. 5-12: Effects of fiber and aggregate orientation on UPV for the beams.

5.3 Comparison between Cylindrical Samples and Beam Samples

Despite the similarities in most of the constituent materials in both cylindrical and beam section samples, there was a significant difference in UPV test results. For instance, the UPV was maximal at 0% fiber volume and decreased gradually for 1% and 2% fiber volumes for the cylindrical samples (Fig. 5-3). However, for the beam samples, the UPV was minimal with 0% fiber, increased rapidly for 1% and 2% fibers, and then decreased for 3% and 4% fibers as, shown by Fig. 5-8.

Comparing the results for the beam and cylindrical samples at 0%, 1%, and 2% fibers, the trends were reversed. That is, for the beam samples, the UPV increased with increasing steel fibers whereas the UPV decreased with increasing steel fibers for the cylindrical samples. Except for the HRWR superplasticizer for 1% and 2% fiber volumes, all the constituent materials were the same for both beams and cylinders. Especially for

0% steel fibers, both beams and cylinders had exactly the same constituent materials (Tables 4-2 and 4-3).

Despite these similarities, the UPV at 0% fiber for the cylinders was higher than that of the beams. The following potential factors could be considered to explain these two discrepancies:

1) Why the UPV at 0% fiber was higher for the cylinders than the beams and
2) Why the trends of UPV for the beams and cylinders were reversed.

The first potential factor for the higher UPV in a cylindrical sample at 0% fiber was the higher bulk density (Table 4-3) than the beam (Table 4-2). This density difference may have arisen from the higher overlaying self-weight of the mix in the cylindrical mold due to its height (8 in), which was twice larger than the height of the beam. Since UPV is basically related to density and elastic behavior of the material, this density variation definitely made a difference.

In addition, during the test, there was a moisture difference between the beam samples and cylindrical samples. That is, the beam samples were tested in a completely air-dried condition since their setting time had already passed. On the other hand, the cylindrical samples were tested in a saturated condition immediately after being taken out of the water bucket. As discussed in Section 5.1.5, the sample with higher moisture content had a higher UPV for the same constituent materials. Therefore, the cumulative effects of these two potential factors (density and moisture) were assumed to be the causes of the difference.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the objective of this study, investigating the responses of ultrasonic pulse velocity within steel fibers reinforced self-compacted concrete, various results were identified in this experiment. UPV concrete testing may be as simple as measuring the dimensions of the test specimens, following the test procedures mentioned in Section 4.4.2. However, interpreting results and drawing conclusions are more difficult and challenging than any other conventional destructive test methods. Understanding the behaviors of ultrasonic wave velocity and its response to various factors within and around the test specimens are very important. Therefore, taking into account these points, the following important conclusions were made from this experiment.

First, although it is not debatable that the addition of steel fibers can make a change on UPV as well as on some basic properties of plain concretes, identifying these changes and deciding the effective amount of fiber to be added are the key issues to be addressed. This study showed that the addition of 2% by volume of randomly distributed steel fibers to a self-compacted plain concrete increased the UPV by 5.6%, provided that sufficient amount of superplasticizer is added. Therefore, 2% volume fraction of steel fibers is the optimum amount to be used in SFR-SCC with the corresponding superplasticizer of 0.416 lb/ft^3. Despite the use of the proper amount of superplasticizer, the UPV value decreased for steel fiber volumes greater than 2%.

Second, the test result revealed that, the UPV was increased with the curing period of the specimens. That is, the UPV increased rapidly from 1-28 days; after that, the slope became gentle or even flat. This implied that UPV is the best tool to estimate the setting time of a concrete matrix.

Third, this study observed that the saturated samples have higher UPV than air dried samples. The result showed that the effect of saturation on UPV became greater with the % volume of steel fibers. Recalling that the more fibers the more voids in a concrete, the voids were filled with water which has more wave propagating capacity than air.

Fourth, the UPV can be improved up to limited amounts of fiber volumes (2%). The reason for the UPV starting to drop after 2% fiber volume is due to the development of more influential voids (Fig. 5-8).

The bulk density was observed to increase continuously with the volume of fibers, regardless of the decrease in UPV (Tables 5-1 and 5-2). The reason is most probably the addition of steel fibers with high specific gravity (7.85), which increase the density by more folds than they decrease the density due to voids initiation. Therefore, density may not be a good parameter to evaluate the quality of SFR-SCC using the UPV test, since it increases continuously regardless of the decrease in UPV and compressive strength.

Fifth, the test result showed that the UPV increased in the direction of the orientation of the fibers and aggregates. Also, the addition of admixtures, such as fly ash, silica fume, and superplasticizer play a significant role in the variations of UPV.

Generally, for limited sources of measurement errors, UPV test is a very reliable, fast, and economical method of concrete flaw detection and, hence, for estimating the design properties of concrete.

6.2 Recommendations

1) Mechanical vibration should be used for fiber volumes beyond 2%.
2) In-depth study is recommended to compare the effect of steel fibers on density, either by increasing the weight or by decreasing the absolute volume due to void initiation.
3) The results obtained from the UPV test are better to use for flaw detection rather than used as a reference value to raise compliance against the design value.
4) Further investigation on the sensitivity of the ultrasonic wave with respect to density, voids/cracks, fiber orientation, and other heterogeneities is highly recommended.
5) Further investigation on the effect of shape (cube or cylindrical) on UPV using the same constituent materials is also advised.
6) The effect of wave path length on UPV using the same mix also needs to be assessed.

APPENDICES

Appendix A: Analytical calculation of volume of voids in cylindrical samples.

- **0% fiber**

$V_T = V_C + V_S$ $V_T = 1647.41\ cm^3$ (measured); $V_S = 0$

$V_V = V_T - V_C$ V_V = Volume of voids

$V_C = W_C/\Upsilon_C$ $W_C = 4064.7$ gm. (measured)

$\Upsilon_C = 2.5\ gm/cm^3$ (measured)

$V_C = 4064.7/2.5 = 1625.88\ cm^3$

$V_V = 1647.41 - 1625.88 = \mathbf{21.5\ cm^3}$

- **1% fiber**

$V_V = V_T - V_C - V_S$ $V_T = 1647.41\ cm^3$

$V_C = W_C/\Upsilon_C = (W_T - W_S)/\ \Upsilon_C$

$= (4097.6 - 567.67)/2.52$

$= 1400.77\ cm^3$

$V_S = W_S/\Upsilon_S = W_S/G_S\Upsilon_W = 567.67/7.85*1 = 72.31\ cm^3$

$V_V = 1647.41 - 1400.77 - 72.31 = \mathbf{174\ cm^3}$

- **2% Fiber**

$V_V = V_T - V_C - V_S$ $V_T = 1647.41\ cm^3$

$V_C = W_C/\Upsilon_C = (W_T - W_S)/\ \Upsilon_C$

$= (4133 - 1135.3)/2.5$

$= 1272\ cm^3$

$V_S = W_S/\Upsilon_S = W_S/G_S\Upsilon_W = 1135.33/7.85*1 = 145\ cm^3$

$V_V = 1647 - 1272 - 145 = \mathbf{230.4\ cm^3}$

Where V_S = volume of steel; V_C = Volume of concrete; V_T = total volume; V_V= volume of voids

Appendix B: Ultrasonic Pulse Velocity (UPV) test data for fiber volume effect and flaw detection.

Sample 1	0% beam			length (mm)	102.5			V (m/s)	V_{avg} (m/s)
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/22/2011				
P4A IR	(dB)	=	-45.5733	0.01260178	-45.60179	-45.5523			
P4A TF	(usecs)	=	25.5506	0.00567038	25.541282	25.55875		4011.648	
P4A FWHM	(usecs)	=	3.697518	0.03039987	3.6446168	3.767264			
Measurement	2								
P4A IR	(dB)	=	-47.516	0.0325703	-47.58035	-47.4585			
P4A TF	(usecs)	=	24.69293	0.01831135	24.659803	24.72576		4150.985	
P4A FWHM	(usecs)	=	4.00601	0.01882911	3.9791094	4.046255			
Sample 2	0% beam			length (mm)	102.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/22/2011				
P4A IR	(dB)	=	-48.9319	0.01432271	-48.96306	-48.9102			
P4A TF	(usecs)	=	24.85832	0.00984563	24.838424	24.88487		4123.367	
P4A FWHM	(usecs)	=	3.795099	0.02289709	3.7528046	3.839577			
Measurement	2								
P4A IR	(dB)	=	-48.2548	0.01952305	-48.28671	-48.2206			
P4A TF	(usecs)	=	24.55025	0.01073563	24.526365	24.56713		4175.11	
P4A FWHM	(usecs)	=	4.261612	0.0363641	4.1879393	4.343365			
									4257.72
Sample 3	0% beam			length (mm)	102.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/22/2011				
P4A IR	(dB)	=	-46.0102	0.03871671	-46.06864	-45.9316			
P4A TF	(usecs)	=	24.41766	0.00971406	24.398436	24.43889		4197.781	
P4A FWHM	(usecs)	=	4.710877	0.05472007	4.6336527	4.824087			
Measurement	2								
P4A IR	(dB)	=	-43.1256	0.02350149	-43.16706	-43.0861			
P4A TF	(usecs)	=	24.01837	0.00506715	24.008685	24.032		4267.568	
P4A FWHM	(usecs)	=	3.363941	0.01516831	3.3319877	3.399731			
Sample 4	0% beam			length (mm)	102.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/22/2011				
P4A IR	(dB)	=	-50.4902	0.2240795	-50.98011	-50.3104			
P4A TF	(usecs)	=	22.29697	0.00909028	22.274824	22.31416		4597.037	
P4A FWHM	(usecs)	=	3.308029	0.03455448	3.2362304	3.357375			
Measurement	2								
P4A IR	(dB)	=	-51.7361	0.09771476	-51.94076	-51.63			
P4A TF	(usecs)	=	22.58592	0.01533698	22.566261	22.62085		4538.226	
P4A FWHM	(usecs)	=	3.915431	0.04600868	3.8377852	4.002224			

Sample 1	1% Beam			length (mm)	102.5			V (m/s)	V_{avg} (m/s)
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/8/2011				
P4A IR	(dB)	=	-51.8394	0.01651589	-51.86374	-51.8035			
P4A TF	(usecs)	=	23.49149	0.00824091	23.471173	23.5064		4363.283	
P4A FWHM	(usecs)	=	4.042183	0.03300327	3.9718047	4.108581			
Measurement	2								
P4A IR	(dB)	=	-43.4052	0.04846036	-43.48946	-43.3351			
P4A TF	(usecs)	=	23.16236	0.00696401	23.14887	23.17398		4425.283	
P4A FWHM	(usecs)	=	4.084557	0.01947952	4.0253899	4.112702			
Sample 2	1% Beam			length (mm)	102.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/8/2011				
P4A IR	(dB)	=	-46.5873	0.01392752	-46.61464	-46.5612			
P4A TF	(usecs)	=	24.34748	0.00785624	24.334729	24.36874		4209.881	
P4A FWHM	(usecs)	=	4.457691	0.03046694	4.4100516	4.513853			
Measurement	2								
P4A IR	(dB)	=	-48.2983	0.02758147	-48.37541	-48.2619			
P4A TF	(usecs)	=	24.18052	0.01017431	24.157362	24.19534		4238.949	
P4A FWHM	(usecs)	=	4.06331	0.03122567	4.0158602	4.129822			
Sample 3	1% Beam			length (mm)	102.5				**4314.94**
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/8/2011				
P4A IR	(dB)	=	-57.687	0.06637191	-57.7875	-57.5695			
P4A TF	(usecs)	=	24.00484	0.01220558	23.986368	24.03275		4269.972	
P4A FWHM	(usecs)	=	3.315947	0.03816984	3.244651	3.387061			
Measurement	2								
P4A IR	(dB)	=	-48.2884	0.0742759	-48.41345	-48.1905			
P4A TF	(usecs)	=	23.70377	0.0162779	23.66793	23.73122		4324.207	
P4A FWHM	(usecs)	=	4.483805	0.06073455	4.3383689	4.600714			
Sample 4	1% Beam			length (mm)	102.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/8/2011				
P4A IR	(dB)	=	-51.2623	0.01761736	-51.30127	-51.2316			
P4A TF	(usecs)	=	24.36102	0.01253127	24.339872	24.38718		4207.542	
P4A FWHM	(usecs)	=	5.475216	0.18557649	5.1150423	5.870268			
Measurement	2								
P4A IR	(dB)	=	-44.475	0.04916299	-44.55944	-44.4025			
P4A TF	(usecs)	=	22.87732	0.00863819	22.857566	22.88984		4480.42	
P4A FWHM	(usecs)	=	3.684071	0.02072886	3.6534188	3.731078			

								V (m/s)	V_{avg} (m/s)
Sample 1	2% Fiber Beam			length (mm)	102.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/10/2011				
P4A IR	(dB)	=	-39.92	0.14766316	-40.05424	-39.5583			
P4A TF	(usecs)	=	23.0873	0.00485861	23.079039	23.09698		4439.67	
P4A FWHM	(usecs)	=	3.272958	0.04954668	3.2119331	3.397625			
Measurement	2								
P4A IR	(dB)	=	-45.2021	0.04585047	-45.27143	-45.1275			
P4A TF	(usecs)	=	22.30709	0.00552443	22.292556	22.31885		4594.951	
P4A FWHM	(usecs)	=	3.491791	0.03723967	3.4264526	3.552123			
Sample 2	2% Fiber Beam			length (mm)	102.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/10/2011				
P4A IR	(dB)	=	-40.9211	0.0244014	-40.95264	-40.8676			
P4A TF	(usecs)	=	22.60077	0.00630647	22.589216	22.61015		4535.244	
P4A FWHM	(usecs)	=	3.596832	0.01117866	3.5715798	3.619268			
Measurement	2								
P4A IR	(dB)	=	-47.1881	0.08958503	-47.38806	-47.0365			
P4A TF	(usecs)	=	21.74889	0.0094501	21.733289	21.76473		4712.885	
P4A FWHM	(usecs)	=	3.068934	0.01576498	3.0258659	3.089291			
Sample 3	2% Fiber Beam			length (mm)	102.5				**4512.19**
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/10/2011				
P4A IR	(dB)	=	-41.6541	0.03754924	-41.72444	-41.6007			
P4A TF	(usecs)	=	22.69233	0.00421447	22.681268	22.69985		4516.945	
P4A FWHM	(usecs)	=	3.486263	0.01468498	3.4448028	3.509486			
Measurement	2								
P4A IR	(dB)	=	-39.5897	0.06689144	-39.67772	-39.472			
P4A TF	(usecs)	=	23.08628	0.00462711	23.077802	23.09442		4439.866	
P4A FWHM	(usecs)	=	3.333358	0.00955242	3.3167832	3.351518			
Sample 4	2% Fiber Beam			length (mm)	102.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1		date casted		2/10/2011				
P4A IR	(dB)	=	-48.1655	0.02331415	-48.20612	-48.1305			
P4A TF	(usecs)	=	22.54786	0.00838009	22.531985	22.56287		4545.887	
P4A FWHM	(usecs)	=	3.677144	0.02574144	3.6254419	3.712684			
Measurement	2								
P4A IR	(dB)	=	-49.3255	0.04163619	-49.39005	-49.2664			
P4A TF	(usecs)	=	23.77065	0.00825673	23.758119	23.7834		4312.04	
P4A FWHM	(usecs)	=	3.317812	0.02502022	3.2782043	3.365446			

							V (m/s)	V_{avg} (m/s)
Sample 1	3% Fiber Beam			length (mm)		102.5		
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		date casted		2/13/2011			
P4A IR	(dB)	=	-52.1524	0.05517933	-52.24031	-52.0623	4242.742	
P4A TF	(usecs)	=	24.1589	0.01384824	24.133682	24.19082		
P4A FWHM	(usecs)	=	4.351088	0.06017413	4.2498141	4.488987		
Measurement	2							
P4A IR	(dB)	=	-41.0956	0.38256681	-41.49988	-40.6848	4395.319	
P4A TF	(usecs)	=	23.32026	0.01025913	23.30379	23.33548		
P4A FWHM	(usecs)	=	3.891449	0.01944298	3.8611374	3.922272		
Sample 2	3% Fiber Beam			length (mm)		102.5		
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		date casted		2/13/2011			
P4A IR	(dB)	=	-46.7822	0.05071134	-46.86139	-46.6994	4498.682	
P4A TF	(usecs)	=	22.78445	0.00936003	22.766984	22.79972		
P4A FWHM	(usecs)	=	3.583149	0.02175724	3.5562134	3.630742		
Measurement	2							
P4A IR	(dB)	=	-45.7494	0.05577149	-45.85537	-45.661	4247.769	
P4A TF	(usecs)	=	24.13032	0.0095113	24.109984	24.14653		
P4A FWHM	(usecs)	=	4.842455	0.03251582	4.7858002	4.910195		
								4481.58
Sample 3	3% Fiber Beam			length (mm)		102.5		
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		date casted		2/13/2011			
P4A IR	(dB)	=	-49.6974	0.04841415	-49.77375	-49.6006	4550.731	
P4A TF	(usecs)	=	22.52385	0.01060507	22.506225	22.54806		
P4A FWHM	(usecs)	=	3.761601	0.04398967	3.6752022	3.853249		
Measurement	2							
P4A IR	(dB)	=	-50.7391	0.22181522	-51.1072	-50.3836	4368.844	
P4A TF	(usecs)	=	23.46159	0.01536896	23.435485	23.48908		
P4A FWHM	(usecs)	=	3.81318	0.02274067	3.7822219	3.861655		
Sample 4	3% Fiber Beam			length (mm)		102.5		
cast date	2/13/2011		test date	10/19/11				
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1							
P4A IR	(dB)	=	-47.0343	0.01802556	-47.0562	-46.9992	4381.069	
P4A TF	(usecs)	=	23.39612	0.00993052	23.381373	23.41729		
P4A FWHM	(usecs)	=	4.422935	0.03882495	4.3454629	4.497947		
Measurement	2							
P4A IR	(dB)	=	-38.8721	0.02050245	-38.91001	-38.8322		
P4A TF	(usecs)	=	23.97343	0.00675436	23.961042	23.98341	4275.566	
P4A FWHM	(usecs)	=	4.324133	0.01824837	4.2970964	4.353577		

Sample 1 4% fiber aged beam								V (m/s)	V_{avg} (m/s)
width of sample (mm)						102.5			
cast date						2/26/2011			
Parameter	(units)		Mean	Stddev	Min	Max		4432.294	
Measurement	1								
P4A IR	(dB)	=	-41.3231	0.03174831	-41.37892	-41.2695			
P4A TF	(usecs)	=	23.12572	0.00569767	23.112509	23.13474			
P4A FWHM	(usecs)	=	3.424877	0.01325969	3.396392	3.448472			
Measurement	2								
P4A IR	(dB)	=	-40.8592	0.01265533	-40.87605	-40.8332		4433.816	
P4A TF	(usecs)	=	23.11778	0.00601337	23.107223	23.12753			
P4A FWHM	(usecs)	=	3.806241	0.01255989	3.7844484	3.833765			
									4442.48
Sample 2 4% fiber aged beam									
width of sample (mm)						102.5			
cast date						2/26/2011			
Parameter	(units)		Mean	Stddev	Min	Max		4664.054	
Measurement	1								
P4A IR	(dB)	=	-45.5221	0.02142208	-45.54728	-45.4771			
P4A TF	(usecs)	=	21.97659	0.0060056	21.9627	21.99039			
P4A FWHM	(usecs)	=	3.345037	0.00990901	3.3291344	3.361744			
Measurement	2								
P4A IR	(dB)	=	-41.5654	0.0129093	-41.59073	-41.5432		4239.758	
P4A TF	(usecs)	=	24.17591	0.00732185	24.161393	24.18884			
P4A FWHM	(usecs)	=	4.781742	0.0206182	4.7440071	4.820982			

Note: IR = Integrated response
TF = Time of flight
FWHM = Full width half max

7th day cylinderical samples test

Sample 1 0% fiber-1/1 cylider sample								
width of sample (mm)			201.5					
cast date			9/21/2012					
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1							
P4A IR	(dB)	=	-57.404	0.9418	-59.6729	-56.9092		
P4A TF	(usecs)	=	42.03934	0.397472	41.18757	42.39301	velocity	4793.129
P4A FWHM	(usecs)	=	41.75592	0.106007	41.48436	42.03157		
Sample 2 1% fiber-1/2 cylider sample								
width of sample (mm)			201.5					
cast date			9/22/2012					
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1							
P4A IR	(dB)	=	-56.7307	0.023438	-56.7714	-56.6835		
P4A TF	(usecs)	=	42.59219	0.03599	42.52355	42.67407	velocity	4730.914
P4A FWHM	(usecs)	=	42.24112	0.017406	42.21326	42.26871		
Sample 3 1% fiber-2/2 cylider sample								
width of sample (mm)			201.5					
cast date			9/22/2012					
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1							
P4A IR	(dB)	=	-61.6105	0.057591	-61.6844	-61.4886		
P4A TF	(usecs)	=	42.70116	0.04377	42.5985	42.77405	velocity	4718.842
P4A FWHM	(usecs)	=	42.56365	0.025446	42.52346	42.62671		
Sample 4 2% fiber-1/2 cylider sample								
width of sample (mm)			201.5					
cast date			9/23/2012					
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1							
P4A IR	(dB)	=	-69.4429	0.518798	-71.6242	-69.2234		
P4A TF	(usecs)	=	44.01259	0.114696	43.56636	44.09668	velocity	4578.235
P4A FWHM	(usecs)	=	44.09168	0.047033	43.96383	44.1692		
Sample 5 2% fiber-2/2 cylider sample								
width of sample (mm)			201.5					
cast date			9/23/2012					
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1							
P4A IR	(dB)	=	-77.5587	1.158456	-80.4547	-76.3171		
P4A TF	(usecs)	=	45.90181	1.360832	44.80459	49.92565	velocity	4389.805
P4A FWHM	(usecs)	=	45.89091	1.398953	45.25594	50.06239		

28th day Cylindrical Sample Test

Sample 1	0% fiber-1/1		width (mm)		201.5				
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-48.7333	0.016519	-48.7656	-48.6986			
P4A TF	(usecs)	=	40.0251	0.009482	40.00807	40.04674			
P4A FWHM	(usecs)	=	3.769377	0.042789	3.684616	3.834036			
Measurement	2							velocity	5010.851
P4A IR	(dB)	=	-50.9257	0.018346	-50.9473	-50.8839			
P4A TF	(usecs)	=	40.40037	0.009839	40.37584	40.41263			
P4A FWHM	(usecs)	=	4.133559	0.035025	4.082062	4.228928			
Sample 2	1% fiber 1/2		width (mm)			201.5			
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-54.5838	0.019835	-54.6289	-54.542			
P4A TF	(usecs)	=	41.72068	0.013964	41.7052	41.75025			
P4A FWHM	(usecs)	=	3.708312	0.035763	3.632355	3.783823			
Measurement	2							velocity	4782.601
P4A IR	(dB)	=	-54.6297	0.025785	-54.6735	-54.5812			
P4A TF	(usecs)	=	42.54309	0.020375	42.49323	42.58177			
P4A FWHM	(usecs)	=	4.896192	0.057582	4.804346	5.013028			
Sample 3	1% fiber 2/2		width (mm)			201.5			
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-54.7227	0.023712	-54.7592	-54.6711			
P4A TF	(usecs)	=	42.4938	0.020033	42.44604	42.52349			
P4A FWHM	(usecs)	=	5.06738	0.101947	4.934674	5.404541			
Measurement	2							velocity	4758.646
P4A IR	(dB)	=	-53.064	1.098672	-55.8649	-52.581			
P4A TF	(usecs)	=	42.19416	0.052847	42.01042	42.22996			
P4A FWHM	(usecs)	=	-9.04998	45.61063	-188.747	5.900067			
Sample 4	2% fiber-1/2 cylinder sample								
width of sample (mm)						201.5			
cast date						9/23/2012			
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-63.9633	0.039538	-64.0158	-63.8686			
P4A TF	(usecs)	=	43.40626	0.023166	43.36643	43.44585			
P4A FWHM	(usecs)	=	3.818085	0.061558	3.706125	3.927783			
Measurement	2							velocity	4644.61
P4A IR	(dB)	=	-54.0267	0.026507	-54.0785	-53.9819			
P4A TF	(usecs)	=	43.36098	0.018605	43.31751	43.39102			
P4A FWHM	(usecs)	=	5.12155	0.066669	4.994775	5.225907			
Sample 5	2% fiber-2/2 cylinder sample								
width of sample (mm)						201.5			
cast date						9/23/2012			
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-57.1117	0.683609	-60.014	-56.9087			
P4A TF	(usecs)	=	43.96493	0.03132	43.91042	44.01898			
P4A FWHM	(usecs)	=	-16.9009	101.6979	-448.965	6.51752			
Measurement	2							velocity	4639.836
P4A IR	(dB)	=	-54.1096	0.023545	-54.1498	-54.0674			
P4A TF	(usecs)	=	42.89158	0.011738	42.86982	42.90978			
P4A FWHM	(usecs)	=	4.129035	0.046222	4.057999	4.201523			

90th Day Cylindrical Samples Test									
Sample 1	0% Fiber		length (mm)	201.5					
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-73.432113	0.332596	-73.7513	-72.229			
P4A TF	(usecs)	=	39.657684	0.056852	39.54557	39.76122			5080.983
P4A FWHM	(usecs)	=	-138.05328	610.2818	-2730.58	9.698151			
Measurement	2						**Avg. Velocity (m/s)**		**5071.61**
P4A IR	(dB)	=	-62.053949	0.04976	-62.1722	-61.9777			
P4A TF	(usecs)	=	39.804515	0.02041	39.77233	39.84051			5062.24
P4A FWHM	(usecs)	=	3.8686399	0.04963	3.784549	4.01228			
Sample 2	1% Fiber		length (mm)	201.5					
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-79.569376	0.663136	-81.184	-79.0008			
P4A TF	(usecs)	=	41.070783	0.126355	40.87986	41.4719			4906.164
P4A FWHM	(usecs)	=	-9.1778913	38.68548	-159.858	4.098612			
Measurement	2						**Avg. Velocity (m/s)**		**4928.99**
P4A IR	(dB)	=	-72.532557	0.131353	-72.7598	-72.2508			
P4A TF	(usecs)	=	40.692188	0.02032	40.64362	40.72394			4951.81
P4A FWHM	(usecs)	=	2.8531455	0.059455	2.783713	2.974969			
Sample 3	1% Fiber		length (mm)	201.5					
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-73.426329	0.780771	-74.5752	-72.2139			
P4A TF	(usecs)	=	40.7756	0.043205	40.5764	40.8976			4941.681
P4A FWHM	(usecs)	=	2.8238039	0.07445	2.71575	2.943625			
Measurement	2						**Avg. Velocity (m/s)**		**4940.86**
P4A IR	(dB)	=	-70.54253	0.680169	-72.7834	-70.1303			
P4A TF	(usecs)	=	40.789226	0.043393	40.70285	40.86154			4940.03
P4A FWHM	(usecs)	=	0.94392013	9.785974	-33.5238	4.255136			
Sample 4	2% Fiber		length (mm)	201.5					
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-80.61813	1.870688	-87.3937	-79.4192			
P4A TF	(usecs)	=	41.641508	0.335078	40.27847	41.8963			4838.922
P4A FWHM	(usecs)	=	-0.35005222	11.24757	-46.0199	4.089096			
Measurement	2						**Avg. Velocity (m/s)**		**4845.36**
P4A IR	(dB)	=	-71.116481	0.575614	-73.5283	-70.8075			
P4A TF	(usecs)	=	41.530959	0.042773	41.44029	41.59435			4851.802
P4A FWHM	(usecs)	=	2.2936319	6.60898	-25.7783	4.010727			
Sample 5	2% Fiber		length (mm)	201.5					
Parameter	(units)		Mean	Stddev	Min	Max			
Measurement	1								
P4A IR	(dB)	=	-77.260628	1.478781	-79.8928	-75.4309			
P4A TF	(usecs)	=	43.202242	1.337456	41.8586	45.35863			4664.11
P4A FWHM	(usecs)	=	-71.674771	209.523	-888.852	4.756909			
Measurement	2						**Avg. Velocity (m/s)**		**4718.82**
P4A IR	(dB)	=	-77.312697	2.994671	-81.238	-72.3898			
P4A TF	(usecs)	=	42.211934	0.345244	41.66574	42.84414			4773.532
P4A FWHM	(usecs)	=	-4.1884972	10.20664	-32.5051	9.577781			

Appendix C: UPV test data for fibers orientation effect analysis

Sample 1	0%-1/2							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		103			
P4A IR	(dB)	=	-52.932	1.08112	-55.802	-52.288		
P4A TF	(usecs)	=	24.4067	0.10176	24.2683	24.66697	**Velocity (m/s)**	4220.15
P4A FWHM	(usecs)	=	-13.391	52.9393	-186.36	5.762285		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-47.647	0.02465	-47.693	-47.60345		
P4A TF	(usecs)	=	23.8216	0.013	23.0824	23.12786	**Velocity (m/s)**	4302.82
P4A FWHM	(usecs)	=	5.30318	0.15468	5.05123	5.635708		
Measurement	3		length (mm)		124			
P4A IR	(dB)	=	-52.197	0.02942	-52.241	-52.12597		
P4A TF	(usecs)	=	27.9614	0.0124	27.712	27.75537	**Velocity (m/s)**	4434.68
P4A FWHM	(usecs)	=	4.14655	0.05412	4.04813	4.270824		
Sample 2	0%-2/2							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		103			
P4A IR	(dB)	=	-56.798	0.03348	-56.864	-56.73729		
P4A TF	(usecs)	=	24.4029	0.01157	24.4907	24.53015	**Velocity (m/s)**	4220.81
P4A FWHM	(usecs)	=	4.12402	0.12054	3.99875	4.576402		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-48.899	0.05952	-48.999	-48.79204		
P4A TF	(usecs)	=	24.409	0.01279	24.3885	24.43839	**Velocity (m/s)**	4199.26
P4A FWHM	(usecs)	=	5.2203	0.03012	5.15368	5.264259		
Measurement	3		length (mm)		120			
P4A IR	(dB)	=	-54.526	0.11151	-54.684	-54.33205		
P4A TF	(usecs)	=	29.3155	0.01742	30.2848	30.3468	**Velocity (m/s)**	4093.4
P4A FWHM	(usecs)	=	4.67335	0.05165	4.56303	4.769961		

Sample 15	4%-1/2							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		102.5			
P4A IR	(dB)	=	-51.223	0.04668	-51.307	-51.1284		
P4A TF	(usecs)	=	24.2437	0.01132	23.7188	23.76451	**Velocity (m/s)**	4227.9
P4A FWHM	(usecs)	=	3.38165	0.0267	3.34697	3.459277		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-57.633	0.05393	-57.728	-57.5042		
P4A TF	(usecs)	=	24.4291	0.02154	25.0891	25.16701	**Velocity (m/s)**	4195.82
P4A FWHM	(usecs)	=	4.44043	0.08275	4.31128	4.634795		
Measurement	3		length (mm)		102.4			
P4A IR	(dB)	=	-46.27	0.21444	-46.629	-45.94099		
P4A TF	(usecs)	=	23.5347	0.00759	23.5181	23.54871	**Velocity (m/s)**	4351.02
P4A FWHM	(usecs)	=	3.54443	0.01998	3.48564	3.572213		
Sample 16	4%-2/2							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		102.5			
P4A IR	(dB)	=	-52.642	0.06798	-52.852	-52.55656		
P4A TF	(usecs)	=	23.9564	0.0188	22.906	22.98625	**Velocity (m/s)**	4278.61
P4A FWHM	(usecs)	=	5.55695	0.36106	4.98137	6.264525		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-39.095	0.1295	-39.316	-38.93451		
P4A TF	(usecs)	=	23.2595	0.00673	23.2503	23.27775	**Velocity (m/s)**	4406.8
P4A FWHM	(usecs)	=	4.05399	0.01895	4.02659	4.099909		
Measurement	3		length (mm)		126			
P4A IR	(dB)	=	-43.194	0.06568	-43.3	-43.07533		
P4A TF	(usecs)	=	29.0677	0.01744	29.0347	29.0992	**Velocity (m/s)**	4334.71
P4A FWHM	(usecs)	=	5.43261	0.031	5.37405	5.48044		

Sample 3	1%-1/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		101.8			
P4A IR	(dB)	=	-48.229	0.02949	-48.293	-48.16236		
P4A TF	(usecs)	=	23.7108	0.00751	23.6941	23.72544	**Velocity (m/s)**	4293.4
P4A FWHM	(usecs)	=	3.13078	0.01645	3.09583	3.149029		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-49.246	0.0971	-49.418	-49.10862		
P4A TF	(usecs)	=	23.8013	0.00918	23.7841	23.82339	**Velocity (m/s)**	4306.49
P4A FWHM	(usecs)	=	4.13464	0.0302	4.09184	4.204152		
Measurement	3		length (mm)		126			
P4A IR	(dB)	=	-53.891	0.04393	-53.944	-53.81164		
P4A TF	(usecs)	=	28.5912	0.01452	28.5676	28.62644	**Velocity (m/s)**	4406.95
P4A FWHM	(usecs)	=	3.66641	0.0295	3.62537	3.730316		
Sample 4	1%-2/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		102.2			
P4A IR	(dB)	=	-58.712	0.05003	-58.809	-58.64684		
P4A TF	(usecs)	=	23.5186	0.01795	23.4871	23.55433	**Velocity (m/s)**	4345.5
P4A FWHM	(usecs)	=	3.81468	0.06449	3.69893	3.954288		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-52.072	0.03738	-52.147	-52.00039		
P4A TF	(usecs)	=	23.2499	0.01037	23.2328	23.27085	**Velocity (m/s)**	4408.63
P4A FWHM	(usecs)	=	3.76424	0.0298	3.7093	3.806479		
Measurement	3		length (mm)		128			
P4A IR	(dB)	=	-47.877	0.01399	-47.894	-47.83857		
P4A TF	(usecs)	=	28.8309	0.01005	28.8113	28.84959	**Velocity (m/s)**	4439.68
P4A FWHM	(usecs)	=	4.32824	0.03078	4.27888	4.385939		
Sample 5	1%-3/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		102			
P4A IR	(dB)	=	-54.869	0.03102	-54.917	-54.80465		
P4A TF	(usecs)	=	23.3037	0.01115	23.2823	23.3239	**Velocity (m/s)**	4377
P4A FWHM	(usecs)	=	3.45648	0.01969	3.41645	3.486988		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-47.492	0.0271	-47.55	-47.44881		
P4A TF	(usecs)	=	23.4252	0.00512	24.2165	24.23405	**Velocity (m/s)**	4375.64
P4A FWHM	(usecs)	=	3.34791	0.01568	3.32101	3.383986		
Measurement	3		length (mm)		102			
P4A IR	(dB)	=	-51.61	0.1337	-51.881	-51.46473		
P4A TF	(usecs)	=	23.1387	0.00565	23.1259	23.14629	**Velocity (m/s)**	4408.2
P4A FWHM	(usecs)	=	3.62975	0.02064	3.5982	3.665824		
Sample 6	1%-4/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		101.6			
P4A IR	(dB)	=	-47.405	0.05792	-47.518	-47.31571		
P4A TF	(usecs)	=	24.3342	0.00673	24.319	24.34654	**Velocity (m/s)**	4175.19
P4A FWHM	(usecs)	=	3.79015	0.02634	3.74417	3.854465		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-51.572	0.06859	-51.701	-51.45641		
P4A TF	(usecs)	=	23.5387	0.0133	23.5113	23.56216	**Velocity (m/s)**	4354.52
P4A FWHM	(usecs)	=	3.91216	0.03622	3.83993	3.982851		
Measurement	3		length (mm)		132			
P4A IR	(dB)	=	-54.719	0.06025	-54.806	-54.62492		
P4A TF	(usecs)	=	30.0416	0.01185	30.0132	30.06174	**Velocity (m/s)**	4393.91
P4A FWHM	(usecs)	=	3.88907	0.03832	3.84859	3.960346		

Sample 7	2%-1/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		102.5			
P4A IR	(dB)	=	-48.061	0.00982	-48.082	-48.037		
P4A TF	(usecs)	=	23.3487	0.01158	23.3256	23.3719	**Velocity (m/s)**	4389.968
P4A FWHM	(usecs)	=	3.74322	0.02267	3.69714	3.77886		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-50.834	0.06983	-50.937	-50.726		
P4A TF	(usecs)	=	23.2072	0.00933	23.4944	23.5324	**Velocity (m/s)**	4416.741
P4A FWHM	(usecs)	=	3.54977	0.02601	3.5032	3.62189		
Measurement	3		length (mm)		129			
P4A IR	(dB)	=	-41.798	0.23125	-42.23	-41.465		
P4A TF	(usecs)	=	28.3995	0.00429	28.292	28.3065	**Velocity (m/s)**	4542.341
P4A FWHM	(usecs)	=	3.09322	0.00685	3.07851	3.10439		
Sample 8	2%-2/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		102.5			
P4A IR	(dB)	=	-45.944	0.09321	-46.113	-45.82		
P4A TF	(usecs)	=	24.0153	0.01066	24.1298	24.1789	**Velocity (m/s)**	4268.12
P4A FWHM	(usecs)	=	5.22543	0.03043	5.17875	5.31231		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-44.538	0.01975	-44.572	-44.506		
P4A TF	(usecs)	=	23.2776	0.0236	23.5528	23.662	**Velocity (m/s)**	4403.377
P4A FWHM	(usecs)	=	5.08552	0.02304	5.05176	5.1417		
Measurement	3		length (mm)		130			
P4A IR	(dB)	=	-51.822	0.04526	-51.909	-51.763		
P4A TF	(usecs)	=	29.2053	0.00945	30.79	30.8225	**Velocity (m/s)**	4451.249
P4A FWHM	(usecs)	=	3.53787	0.02713	3.46786	3.59098		
Sample 9	2%-3/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		103.5			
P4A IR	(dB)	=	-50.335	0.10616	-50.537	-50.184		
P4A TF	(usecs)	=	23.177	0.01248	23.1579	23.1975	**Velocity (m/s)**	4465.633
P4A FWHM	(usecs)	=	3.60076	0.03076	3.56009	3.6741		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-44.302	0.15285	-44.585	-44.058		
P4A TF	(usecs)	=	22.8074	0.00689	22.7909	22.8193	**Velocity (m/s)**	4494.16
P4A FWHM	(usecs)	=	3.01516	0.01003	2.99222	3.02813		
Measurement	3		length (mm)		132.5			
P4A IR	(dB)	=	-52.274	0.08874	-52.42	-52.138		
P4A TF	(usecs)	=	29.2724	0.01302	28.2495	28.2954	**Velocity (m/s)**	4526.449
P4A FWHM	(usecs)	=	4.46179	0.06785	4.27897	4.55665		
Sample 10	2%-4/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		103			
P4A IR	(dB)	=	-52.382	0.08509	-52.516	-52.248		
P4A TF	(usecs)	=	24.016	0.01379	24.1873	24.2424	**Velocity (m/s)**	4288.799
P4A FWHM	(usecs)	=	4.17287	0.05245	4.08873	4.29868		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-51.365	0.12634	-51.581	-51.168		
P4A TF	(usecs)	=	23.1724	0.00739	23.4609	23.4886	**Velocity (m/s)**	4423.357
P4A FWHM	(usecs)	=	3.25276	0.0147	3.22864	3.27602		
Measurement	3		length (mm)		128			
P4A IR	(dB)	=	-49.867	0.02497	-49.908	-49.828		
P4A TF	(usecs)	=	28.228	0.01177	28.2047	28.2485	**Velocity (m/s)**	4534.506
P4A FWHM	(usecs)	=	3.54004	0.02529	3.49869	3.58398		

Sample 11	3%-1/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		102.8			
P4A IR	(dB)	=	-47.397	0.08062	-47.532	-47.292		
P4A TF	(usecs)	=	24.108	0.00882	24.094	24.1244	**Velocity (m/s)**	4264.146
P4A FWHM	(usecs)	=	3.52552	0.01994	3.49687	3.55448		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-43.624	0.11263	-43.782	-43.431		
P4A TF	(usecs)	=	23.5256	0.00755	23.9108	23.9389	**Velocity (m/s)**	4356.959
P4A FWHM	(usecs)	=	3.8968	0.01889	3.85982	3.94309		
Measurement	3		length (mm)		124			
P4A IR	(dB)	=	-61.838	0.04209	-61.934	-61.754		
P4A TF	(usecs)	=	28.3091	0.01883	28.2782	28.3427	**Velocity (m/s)**	4380.211
P4A FWHM	(usecs)	=	3.89029	0.06627	3.77506	4.0602		
Sample 12	3%-2/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		103			
P4A IR	(dB)	=	-48.508	0.0314	-48.564	-48.45		
P4A TF	(usecs)	=	24.1966	0.02221	24.5224	24.5915	**Velocity (m/s)**	4256.796
P4A FWHM	(usecs)	=	5.40712	0.07886	5.29062	5.54892		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-46.896	0.22673	-47.307	-46.575		
P4A TF	(usecs)	=	23.7727	0.01783	23.7384	23.7996	**Velocity (m/s)**	4311.668
P4A FWHM	(usecs)	=	4.64654	0.03125	4.57713	4.70994		
Measurement	3		length (mm)		134			
P4A IR	(dB)	=	-53.171	0.03471	-53.237	-53.097		
P4A TF	(usecs)	=	30.1501	0.02499	30.0865	30.1853	**Velocity (m/s)**	4444.431
P4A FWHM	(usecs)	=	5.88511	0.26723	5.49001	6.52417		
Sample 13	3%-3/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		103.2			
P4A IR	(dB)	=	-58.293	0.03028	-58.376	-58.246		
P4A TF	(usecs)	=	24.3492	0.01569	24.7288	24.7729	**Velocity (m/s)**	4238.339
P4A FWHM	(usecs)	=	3.81281	0.03809	3.73113	3.9141		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-48.349	0.0459	-48.434	-48.265		
P4A TF	(usecs)	=	23.8413	0.01076	24.3204	24.3626	**Velocity (m/s)**	4299.264
P4A FWHM	(usecs)	=	3.70578	0.02206	3.66746	3.7362		
Measurement	3		length (mm)		132			
P4A IR	(dB)	=	-54.581	0.03444	-54.64	-54.51		
P4A TF	(usecs)	=	29.7286	0.01645	30.6831	30.7519	**Velocity (m/s)**	4440.166
P4A FWHM	(usecs)	=	4.91266	0.05398	4.83067	5.00432		
Sample 14	3%-4/4							
Parameter	(units)		Mean	Stddev	Min	Max		
Measurement	1		length (mm)		103			
P4A IR	(dB)	=	-60.759	0.03274	-60.838	-60.696		
P4A TF	(usecs)	=	23.8842	0.01478	23.8588	23.9072	**Velocity (m/s)**	4312.467
P4A FWHM	(usecs)	=	3.45442	0.03846	3.37468	3.52976		
Measurement	2		length (mm)		102.5			
P4A IR	(dB)	=	-50.999	0.04872	-51.089	-50.927		
P4A TF	(usecs)	=	23.283	0.00822	23.8696	23.9016	**Velocity (m/s)**	4402.355
P4A FWHM	(usecs)	=	3.98313	0.0415	3.88179	4.05693		
Measurement	3		length (mm)		132			
P4A IR	(dB)	=	-51.952	0.06584	-52.083	-51.865		
P4A TF	(usecs)	=	29.8949	0.01524	29.8524	29.9169	**Velocity (m/s)**	4415.47
P4A FWHM	(usecs)	=	4.18266	0.02563	4.14233	4.23508		

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