Parte II: Anexos

Desarrollo y aplicación de un método automatizado para el análisis de datos de un dispositivo de monitorización continua de la hidratación de mortero y hormigón mediante señales de ultrasonidos de banda ancha

Anexo A

A. Hormigón

A.1 Cemento portland

A.1.1 Generalidades

En general, se llaman conglomerantes hidráulicos aquellos productos que, amasados con el agua, fraguan y endurecen tanto expuestos al aire como sumergidos en agua, por ser estables en tales condiciones los compuestos resultantes de su hidratación. Los conglomerantes hidráulicos más importantes son los cementes que de una manera general pueden clasificarse en cementos portland y cementos especiales. Los cementos portland se obtienen por molturación conjunta de su clinker y de la cantidad adecuada de regulador de fraguado que es, normalmente, piedra de yeso natural. Se llama clinker de cemento portland al producto que se obtiene al calcinar hasta fusión parcial (unos 1400º C a 1500º C de temperatura) mezclas muy íntimas, preparadas artificialmente de calizas y arcillas, hasta conseguir la combinación casi total de sus componentes.

A.1.2 Composición química

Las características y propiedades del cemento portland están íntimamente ligadas a su composición química y a su constitución potencial. La primera se determina por análisis y viene expresada en forma de óxidos. La composición química media de un cemento portland puede ser la mostrada en la *Tabla A.1.*

Cal combinada	CaO	62,5%
Sílice	SiO_2	21,0%
Alúmina	Al_2O_3	6,5%
Hierro	Fe_2Al_3	2,5%
Azufre	SO_3	2,0%
Cal libre	CaO	2,0%
Magnesia	MgO	2,0%
Perdida al fuego	P.F.	2,0%
Residuo insoluble	R.I.	1,0%
Alcalis	$Na_2O + K_2O$	0,5%

Tabla A.1 Composición química del cemento portland

Los cuatro primeros componentes son los principales del cemento, de carácter básico la cal y de carácter ácido los otros tres. Los componentes restantes son los indeseables de cemento.

- Óxido cálcico libre, CaO: La cal libre y el hidróxido cálcico coexisten normalmente en el cemento anhidro. Una parte de la primera se hidrata y pasa a la segunda durante el amasado, pero si el contenido en CaO libre del cemento es superior al 1,5 o 2 %, queda otra parte capaz de hidratarse en el trascurso del endurecimiento, lo que puede producir fenómenos expansivos.
- Óxido magnésico, MgO: La magnesia puede presentarse en el clinker en estado vítreo o en estado cristalizado, siento esta forma realmente peligrosa, debido a su lenta hidratación para pasar a hidróxido magnésico $Mg(OH)_2$ en un proceso de carácter expansivo.

- Azufre, SO_3: Proviene de la adición de piedra de yeso que se hace al clinker durante la molienda para regular su fraguado y a veces del combustible usado en el horno. Un exceso de SO_3 puede producir el fenómeno de falso fraguado.
- Perdida al fuego: Cuando su valor es apreciable, proviene de adiciones de naturaleza caliza o similar.
- Residuo insoluble: Proviene de la presencia de adiciones de naturaleza silícea.
- Alcalis: Provienen en general de las materias primas y se volatilizan en buena parte, encontrándose luego en el polvo de los humos de las fábricas de cementos.

A.1.3 Composición potencial

Los cuatro componentes principales anteriormente (cal (C), sílice (S), alúmina (A) y hierro (F)) no se encuentran libremente en el cemento sin combinados formando silicatos aluminatos y ferritos cálcicos, que son los constituyentes hidráulicos del mismo o componentes potenciales. El cálculo de la composición potencial del clinker puede realizarse mediante las fórmulas clásicas de Bogue, aunque existen dudas sobre su precisión en cementos. La *Tabla A.2* muestra la composición de un clinker de cemento portland de tipo medio.

Silicato tricálcico	C_3S	40 a 50%
Silicato bicálcico	C_2S	20 a 30%
Aluminato tricálcico	C_3A	10 a 15%
Aluminoferrita tetracálcico	C_4AF	5 a 10%

Tabla A.2 Composición media del clinker de cemento portland

A continuación se comentan brevemente los cuatro componentes citados:

- Silicato tricálcico, C_3S: Es el compuesto activo por excelencia del clinker, porque desarrolla una resistencia inicial elevada, siendo su calor de hidratación igualmente elevado. Su fraguado es lento y su endurecimiento bastante rápido. Por ello aparece en gran proporción en los cementos de endurecimiento rápido y en los de altas resistencias iniciales.
- Silicato bicálcico, C_2S: Es el componente que comunica su resistencia a largo plazo, al ser lento su fraguado y muy lento su endurecimiento. Su calor de hidratación es el más bajo de los cuatro y su estabilidad química es mayor que la del SC_3.
- Aluminato tricálcico, C_3A: Suministra al cemento un calor de hidratación muy grande, elevadísima velocidad de fraguado y gran retracción, por lo que es el compuesto que gobierna las resistencias a corto plazo. Con el objeto de frenar la rápida reacción del C_3A con agua y regular el tiempo de fraguado del cemento, se añade al clinker un sulfato.
- Aluminoferrita tetracálcico, C_4AF: No participa prácticamente en las resistencias mecánicas y su presencia se debe a la necesidad de utilizar fundentes que contienen hierro en la fabricación del clinker. Tiene un pequeño calor de hidratación y gran velocidad de fraguado.

A.1.4 Características físicas y mecánicas

Las características físicas y mecánicas más importantes son: finura de molido, peso específico, fraguado, expansión y resistencia mecánica.

- Finura de molido: es una característica íntimamente ligada al valor hidráulico del cemento, ya que influye decisivamente en la velocidad de las reacciones químicas que tienen lugar durante su fraguado y primer endurecimiento. Al entrar en contacto con el agua los granos de cemento solo se hidratan en una profundidad de 0.01 mm, por lo que si los granos fueran muy gruesos el rendimiento del proceso sería muy pequeño. Si el cemento posee una finura excesiva su retracción y calor de graduado son muy altos, hecho que resulta perjudicial, mientras que una mayor finura del cemento favorece el aumento de resistencia mecánica. Por tanto es necesario llegar a una situación de compromiso en el que el cemento portland debe estar finamente molido, pero no en exceso.
- Peso específico: El peso específico real varía muy poco de unos cementos a otros oscilando entre 3 y 3,15 g/cm^3.
- Fraguado: La velocidad de fraguado de un cemento se establece por las normas estableciendo un periodo de tiempo a partir del amasado dentro del cual se produce en inicio y el final del fraguado. Ambos conceptos se definen de forma arbitraria mediante la aguja de Vicat ya que el fraguado es un proceso continuo que se inicia al amasar el cemento y se prolonga por el endurecimiento sin solución de continuidad.
- Expansión: puede medirse por el método del autoclave o de las agujas de Chatelier y pone de manifiesto a corto plazo el carácter más o menos expansivo que tendrá un cemento a largo plazo debido a la existencia de magnesia o de cal libre en exceso.
- Resistencia mecánica: la resistencia mecánica a compresión y flexotracción a 3,7 y 28 días de un hormigón será tanto mayor cuanto mayor sea la del cemento empleado, pero esta característica que debe buscarse pues en ocasiones perjudica a otro tipo de resistencias como la durabilidad.

A.2 Agua, áridos y aditivos

A.2.1 Agua de amasado y de curado

El agua de amasado juega un doble papel en el hormigón. Por un lado, participa en las reacciones de hidratación del cemento. Por otro, confiere al hormigón la trabajabilidad necesaria para una correcta puesta en obra. La cantidad de agua de amasado debe limitarse al mínimo estrictamente necesario, ya que el agua en exceso se evapora y crea una serie de huecos en el hormigón (capilares) que disminuyen su resistencia, pero, por otra parte, no puede disminuirse excesivamente el contenido en agua, pues podrían obtenerse masas poco trabajables y de difícil colocación en obra.

El agua de curado, durante el proceso de fraguado y primer endurecimiento del hormigón tiene por objeto evitar la desecación, mejorar la hidratación del cemento e impedir una retracción prematura.

A.2.2 Áridos

Como áridos para la confección de hormigones pueden emplearse arenas y gravas naturales o procedentes de machaqueo, que reúnan en igual e superior grado las características de resistencia y durabilidad que se le exijan al hormigón. Suelen preferirse los áridos de tipo silíceo (gravas y arenas de río o cantera) y los que provienen de machaqueo de rocas volcánicas (basalto, andesita, etc.) o de calizas sólidas y densas. Las rocas sedimentarias en general (calizas, dolomitas, etc.) y las volcánicas sueltas (pómez, toba, etc.) pueden ser objeto de análisis previo. No deben emplearse áridos que provengan de calizas blandas, feldespatos, yesos, piritas o rocas poco friables ni porosas.

Se denomina grava o árido grueso a la fracción mayor de 5 mm y arena o árido fino a la menor de 5 mm. La arena suele dividirse a partir de los 2 mm, en arena gruesa y arena fina, llamándose polvo o finos de arena a la fracción inferior a 0,08 mm. La arena es el árido de mayor responsabilidad. A diferencia de la grava, el agua e incluso el cemento, puede decirse que no es posible hacer un buen hormigón sin una buena arena.

Los áridos pueden ser rodados o machacados. Los primeros proporcionan hormigones más dóciles y trabajables, requiriendo menos cantidad de agua que los segundos. Los machacados confieren al hormigón fresco cierta acritud que dificulta su puesta en obra, una mayor resistencia a tracción y una mayor resistencia química.

A.2.3 Aditivos

Se llaman aditivos a aquellos productos que se incorporan al hormigón fresco con objeto de mejorar alguna de sus características (facilitar su puesta en obra, regular su proceso de fraguado, endurecimiento, etc.). Su dosificación en general inferior a un 5 % del peso del cemento, requiere un cuidado especial, ya que, de no ser conveniente pueden influir en el hormigón de forma indeseable, a veces opuesta a la que se quería conseguir con el aditivo. Además de su acción principal o específica, los aditivos suelen ejercer otras acciones secundarias, favorables o desfavorables. Como tales acciones dependen fundamentalmente del resto de los componentes del hormigón, conviene realizar en cada caso, ensayos previos de carácter comparativo. En el mercado existen multitud de aditivos que pueden clasificarse en las siguientes categorías:

- Aceleradores: Son productos que añadidos, al hormigón, adelantan el fraguado o el endurecimiento del mismo, y en general, ambos procesos a la vez. El empleo de aceleradores tiene por objeto, en general, reducir el tiempo de de desmoldeo o desencofrado, lo que adquiere gran importancia en la prefabricación.
- Retardadores: Son productos empleados para retardar el fraguado del hormigón. En general las resistencias de compresión tempranas (1 a 3 días) suelen verse disminuidas, pero no así las de 28 o 90 días, que pueden incluso verse aumentadas. Los retardadores son de utilidad en tiempo caluroso o cuando la distancia de trasporte del hormigón fresco es grande. Suelen aumentar la retracción del hormigón y conviene realizar con ellos ensayos previos en obra, ya que su acción es muy sensible a las condiciones particulares de cada obra, en especial con las dosis de cemento y la relación W/C.
- Plastificantes: Los plastificantes son aditivos que aumentan la docilidad y trabajabilidad del hormigón. Esto permite emplear masas que de otra forma sería casi imposible colocar en obra, o bien reducir el agua de amasado en los hormigones en beneficio de su resistencia o de las dosificación del cemento.
- Aireantes: Ocluyen en la masa del hormigón infinidad de burbujas de aire, de 20 a 200 micras de diámetro, uniformemente repartidas y siguiendo una curva granulométrica continua que se solapa con la del cemento y finos de arena, las cuales interceptan la red capilar del hormigón endurecido, mejorando así su resistencia a las heladas y a los agentes agresivos.
- Plastificantes-aireantes: De forma general puede decirse que todo plastificante reductor de agua es en alguna medida aireante, siendo también cierta la recíproca. No obstante existen productos comerciales que específicamente poseen un carácter mixto, reuniendo las ventajas de ambos tipos de aditivos.
- Otros aditivos: Existen multitud de otros productos como impermeabilizadores, expansivos o compensadores de retracción, gasificantes, endurecedores de superficie, colorantes, inhibidores de corrosión, insecticidas, fungicidas, etc [18].

A.3 Hidratación

A.3.1 Calor de hidratación

La pasta de cemento se calienta, particularmente durante el fraguado y el comienzo del endurecimiento del hormigón. En otras palabras, las reacciones de hidratación son exotérmicas y el calor emitido a temperatura constante es una indicación directa del grado de hidratación. La *Figura A.1* muestra la evolución típica del calor emitido con el tiempo después del amasado. Inmediatamente tras el amasado hay un pico alto pero corto (A) que dura apenas unos minutos. Rápidamente se reduce hasta un valor constante llamado periodo durmiente, donde el cemento es relativamente inactivo, periodo que puede durar hasta 2 o 3 horas. Entonces el calor emitido empieza a aumentar considerablemente durante el fraguado inicial ya alcanza un pico ancho (B) tras el fraguado final. Entonces las reacciones se ralentizan, aunque a veces aparece un pico estrecho (C) tras uno o dos días. Las reacciones de hidratación que causan este comportamiento envuelven a las cuatro fases principales del cemento. Los procesos físicos y químicos que tienen lugar durante la formación de los productos sólidos de la pasta de cemento endurecida son complejos, pero pueden ser simplificados en las siguientes descripciones.

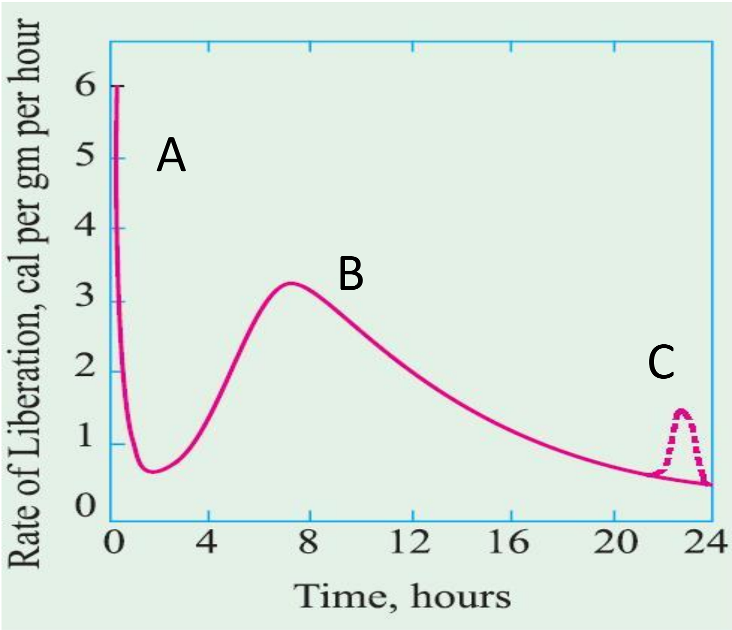


Figura A.1 Calor emitido durante la hidratación del cemento

A.3.2 Reacciones químicas

La principal contribución al primer pico corto e intenso A es la rehidratación hemihidrato de sulfato de calcio, que proviene de la descomposición del yeso en el proceso de molienda:

$$2CS0.5H + H = 2CSH_2 \quad (H{=}H_2O \text{ en nomenclatura abreviada})$$

Otras contribuciones a este pico provienen de la hidratación de la cal libre, calor de humectación, calor de disolución y las reacciones iniciales de las fases de aluminato.

El comportamiento de los aluminatos es particularmente importante en las primeras etapas de la hidratación. En forma pura el C_3A reacciona muy violentamente con agua, que produce una rigidización inmediata de las pasta. Esto debe de ser evitado, y por eso el yeso es añadido al clinker. La reacción inicial del yeso y el C_3A es la siguiente:

$$C_3A + 3CSH +26H \rightarrow C_3A3CSH_{32}$$

El producto, sulfoaluminato de calcio, es conocido como etringita. Aunque la etringita es insoluble y cristaliza, la reacción es mucho más lenta que la del C_3A solo, y los problemas de falso fraguado son evitados.

Normalmente la cantidad de yeso añadida representa un 5 o 6% del peso del cemento, al consumirse, la etringita se transforma progresivamente a monosulfoaluminato de calcio, que tiene un contenido de sulfato menor, y si finalmente todo el yeso se consume antes que el C_3A, el hidrato directo C_3AH_6 se forma. Estor produce el tercer pico estrecho C que puede ocurrir entre 2 y 3 días tras el comienzo de la hidratación.

La fase C_4AF reacciona en escalas similares de tiempo y la reacción implica un producto intermedio con yeso. Los productos tienen una composición imprecisa y variable, pero incluyen distintas formas de sulfato que pueden ser aproximadas por $C_3(A.F).3CS.H_{32}$ y $C_3(A.F).3CS.H_{16}$ similares a los productos del C_3A. Las reacciones de los productos tienen poca significancia en el comportamiento general del cemento.

Como se ha visto, los dos silicatos de calcio C_2S y C_3S forman la base del cemento anhidro y sus productos de hidratación dotan a la pasta de cemento endurecida sus propiedades más significantes para la ingeniería como resistencia y rigidez. Sus reacciones y velocidad de reacción dominan las propiedades de la pasta de cemento y del hormigón y son extremadamente importantes.

El C_3S (o la alita) reacciona más rápido, produciendo silicato tricálcico hidratado y hidróxido de calcio:

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$$

La mayoría del pico principal B en la evolución del calor emitido proviene de esta reacción, y es el silicato de calcio hidratado (normalmente designado como C-S-H) responsable de la resistencia de la pasta de cemento endurecida.

El C_2S (o belita) reacciona más lentamente, pero produce productos idénticos:

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH$$

Esta reacción contribuye poco en el calor emitido pero contribuye de manera muy importante en la resistencia mecánica del hormigón a largo plazo.

A.3.3 Proceso físico

Los procesos físicos que ocurren durante la hidratación y la microestructura resultante de la pasta de cemento endurecida son tanto o más importantes que las reacciones químicas, y numerosos estudios mediante microscopía electrónica analítica han sido realizados. La *Figura*

A.2 ilustra el proceso de hidratación de un grano de cemento en un en un entorno acuoso, donde las principales características son:

- El proceso tiene lugar en la interfase sólido-líquido, donde los productos sólidos se depositan alrededor disminuyendo el núcleo de cemento anhidro en cada grano de cemento
- Los productos de hidratación rápidos forman una capa en la superficie del grano de cemento que actúa como barrera para otras reacciones durante el periodo durmiente
- El periodo durmiente acaba cuando esta capa se destruye por un incremento de la presión interna por ósmosis o por cristales de hidróxido de calcio permitiendo aumentar considerablemente la reacción de hidratación.
- Los productos de hidratación, conocidos como gel, consisten en:
    - Una masa amorfa, mayormente compuesta por C-S-H de partículas pequeñas irregulares y fibrosas, con una superficie específica del orden de 200.000 m^2/kg.
    - Grandes cristales hexagonales de hidróxido cálcico interespaciados en la matriz fibrosa.
- El gel contiene muchos poros entre la matriz fibrosa pero mientras el proceso de hidratación evoluciona, nuevos productos son depositados en la matriz existente, reduciendo la porosidad del gel.
- La velocidad de reacción disminuye tras el pico B debido a la dificultad de difusión del agua a través de los productos hidratados hasta el cemento anhidro.
- Los productos depositados cerca de la interfase cemento fresco/agua son más densos que los depositados fuera de ella
- Cuando la hidratación se ha completado:
    - La porosidad del gel alcanza un límite inferior del 28 %.
    - El volumen de productos de hidratación es algo mayor que dos veces el volumen del cemento anhidro, pero solo entorno a 2/3 del volumen total del cemento anhidro y agua que ha consumido

En realidad la hidratación ocurre simultáneamente en una masa de granos de cemento y agua de amasado y los productos de hidratación interactúan y compiten por el mismo espacio. Una característica importante es que la hidratación tiene lugar a un volumen casi constante [3].

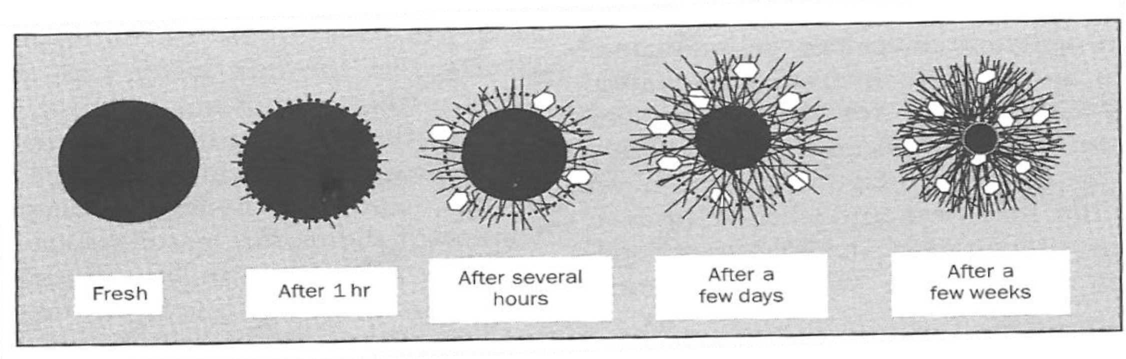


Figura A.2 Hidratación de un grano de cemento (Fuente:[3])

Anexo B

B. Algoritmo AIC

B.1 Introducción

La determinación del tiempo de llegada de una señal es una tarea importante en varios campos de la ciencia. La sismología y la medida de emisiones acústicas son campos que usan el fenómeno de energía potencial elástica que es transformada en ondas elásticas debido a la fractura repentina en un cuerpo rígido. El tiempo de llegada es seleccionado como el punto donde primero aparece una diferencia con el ruido, aunque un analista experimentado normalmente lo desplazaría ligeramente hacia atrás en el tiempo. La forma más simple de determinar el tiempo de llegada es mediante un umbral de amplitud. Sin embargo, en señales con baja amplitud y/o señales con altos niveles de ruido no es posible aplicar este método. Un método autorregresivo AIC produce resultados fiables para emisiones acústicas y señales US con una tasa acierto relativamente alta. El problema de las señales US en hormigón es que la señal y el ruido tienen normalmente el mismo rango de frecuencias. Además la relación señal/ruido no es constante durante los experimentos.

En algoritmo AIC la determinación del tiempo de llegada de la señal se realiza en 2 etapas:

- Determinación del tiempo preliminar de llegada: Se calcula una envolvente de la señal recibida mediante la transformada Hilbert, que es posteriormente cuadratizada y normalizada. El tiempo preliminar de llegada se determina aplicando un umbral simple a dicha envolvente normalizada.
- Determinación del tiempo exacto de llegada: Se calcula la función AIC en una ventana entorno al tiempo de preliminar de llegada, y el mínimo de esta función es el tiempo exacto de llegada de la señal US que permite determinar su velocidad.

B.2 Transformada Hilbert de la señal

El método autorregresivo AIC obtiene picos (los picos significan tiempos de llegada de señal determinados) de mejor calidad si la función AIC es solamente aplicada a la parte de la señal que contiene la llegada. Por eso, la llegada de la señal el calculada preliminarmente usando la trasformada Hilbert. La transformada genera una cierta envolvente de la señal. La transformada Hilbert $\overline{R}(t)$ de una función real dependiente del tiempo R(t) está definida como:

$$\overline{R}(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{R(u)}{t-u} du = H\{R(t)\}$$

donde t denota el tiempo y la singularidad en u=t es tratada tomando el valor de la integral con el principio de Cauchy. La transformada Hilbert está representada por una integral de convolución, es decir, que la transformada Hilbert es una función de transferencia causal que se comporta como un filtro y la transformada de una señal por la transformada Hilbert genera un desfase de π/2. La función envolvente temporal puede ser calculada como:

$$E(t) = \sqrt{R(t)^2 + \overline{R}(t)^2}$$

Esta envolvente es usada para determinar de manera preliminar la llegada de la señal mediante un umbral simple. Cada envolvente es cuadratizada y normalizada, para que un valor umbral constante pueda ser aplicado a todas las señales, como muestra la *Figura B.1a* y *B.1b*. Una ventana de varios cientos de muestras (por ejemplo 400 antes y 150 después de este punto) son tomadas de la señal, y solamente con ellas es calculada la función AIC para determinar el tiempo de llegada de la señal.

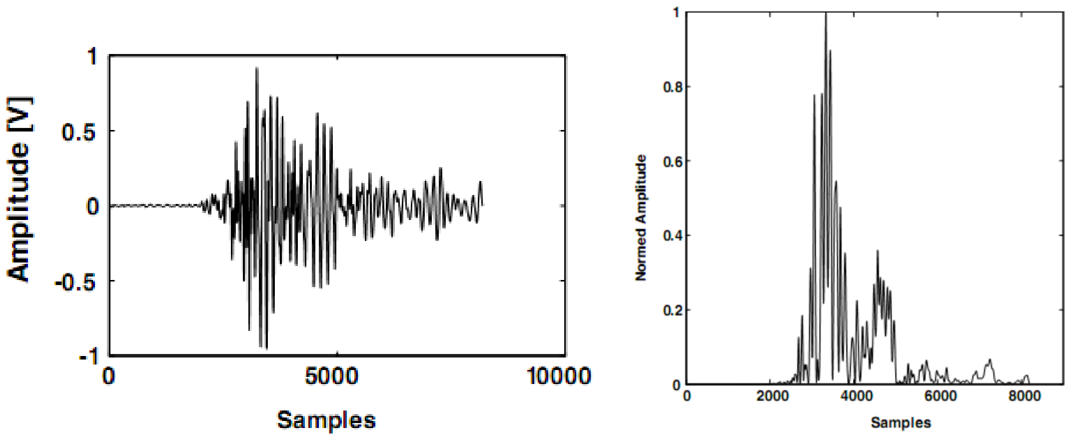


Figura B.1a y B.1b Señal y su envolvente cuadratizada y normalizada (Fuente:[12])

B.3 Función AIC

El tiempo de llegada exacto es determinado mediante el cálculo de la función AIC directamente de la señal:

$$AIC(t_w) = t_w \log(var(R_w(t_w,1))) + (T_w - t_w - 1) \log(var(R_w(1+t_w, T_w)))$$

donde el subíndice w de R_w denota que no toda la señal ha sido tomada sino solo la ventana que contiene la llegada de la señal. T_w es la última muestra de la señal seleccionada, t_w toma los valores de todas las muestras de R_w y var denota la función varianza. El término $R_w(t_w,1)$ significa que la función varianza es solo calculada para todas las muestras entre la primera y el valor actual de t_w, mientras que $R_w(1+t_w, T_w)$ significa que todas las muestras entre $1+t_w$ y T_w son seleccionadas. El mínimo global de la función AIC define el punto de llegada de la señal exacto, como muestra la *Figura B.2* [12].

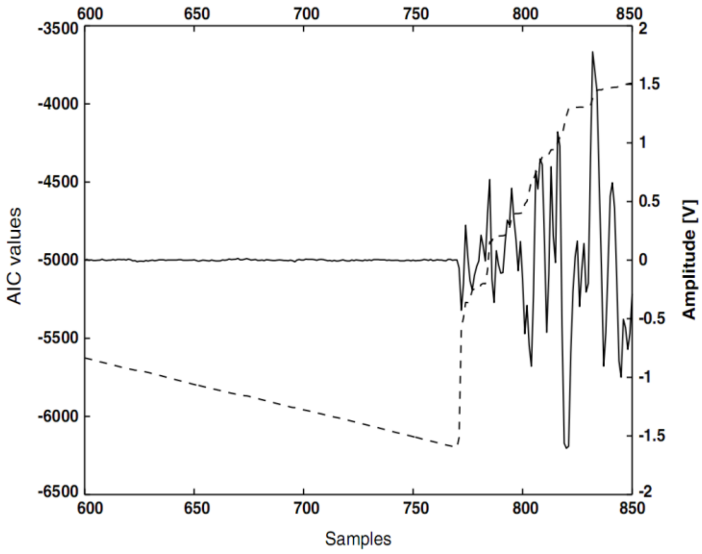


Figura B.2 Señal y su función AIC (Fuente:[12])

Anexo C

C. Analysis of the previous data treatment of Freshcon

C.1 Freshcon

At the Institute of Construction Materials (IWB), University of Stuttgart, an apparatus called Freshcon (*Figure C.1*) was developed aimed at investigating the setting and hardening of cement-based materials in quality assurance.

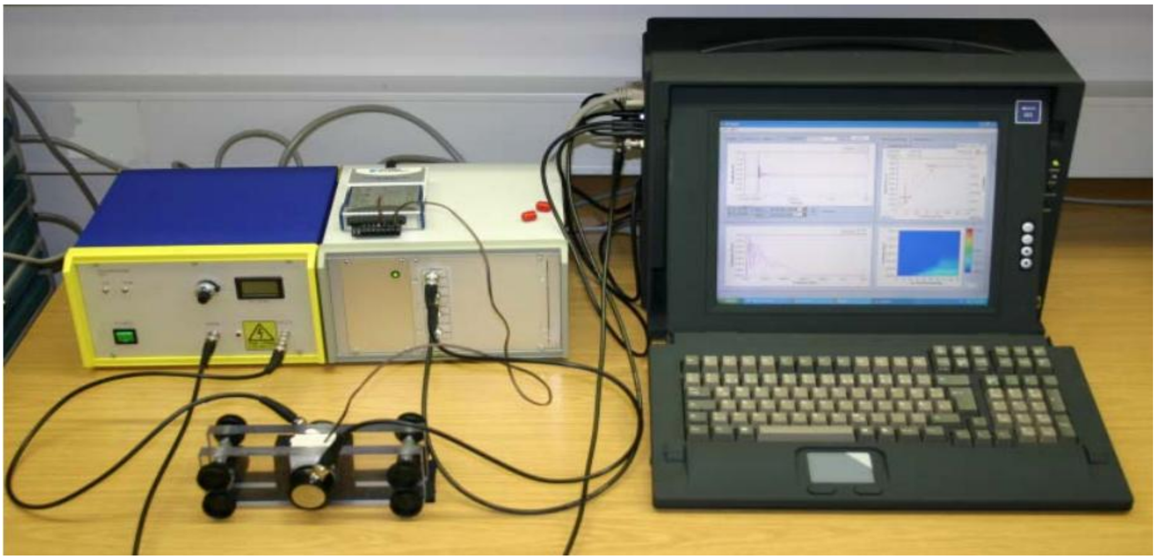


Figure C.1 Freshcon device (Source:[6])

The approach is based on the observation of waves transmitted through mortar or concrete during setting and hardening. The ultrasound wave is recorded and analyzed during the hardening of the material quasi continuously. The waveform as well as wave parameters like travel time (related to the wave velocity), amplitude (related to the wave energy) and frequency content of the signal are influenced by the elastic properties of the material. Cement based materials like concrete and mortar are changing its status from a suspension to a water saturated porous media during hardening. This change can be observed recording transient waves transmitted through the material. Usually, these transients are recorded in certain intervals to document the changes.

The container (*Figure C.2*) consists of two polymethacrylate (PMMA) walls which are tied together by four screws with spacers. The big container or holder (a) has a distance of approximately 55 mm between transducers. The small container or holder (b) has a distance of approximately 20 mm [7].

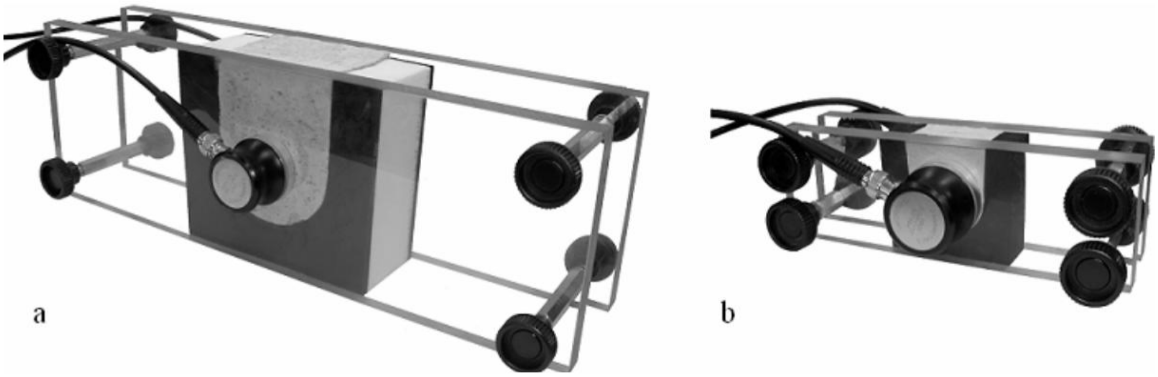


Figure C.2 Freshcon big (a) and small (b) container

C.2 Emitted signal

The Freshcon user can choose between a broad range of emitted US pulses. In this research program, the minimum pulse width is chosen in order to have a better resolution in the velocity measures. A pulse of 2.5µs and amplitude of 800 V is sent from the sender through the cementitous mixture sample. This pulse has approximately the frequency spectrum showed in *Figure C.3*, whose maximum frequency peak is around 450 kHz, and a maximum frequency with amplitude bigger than -30dB of around 700 kHz.

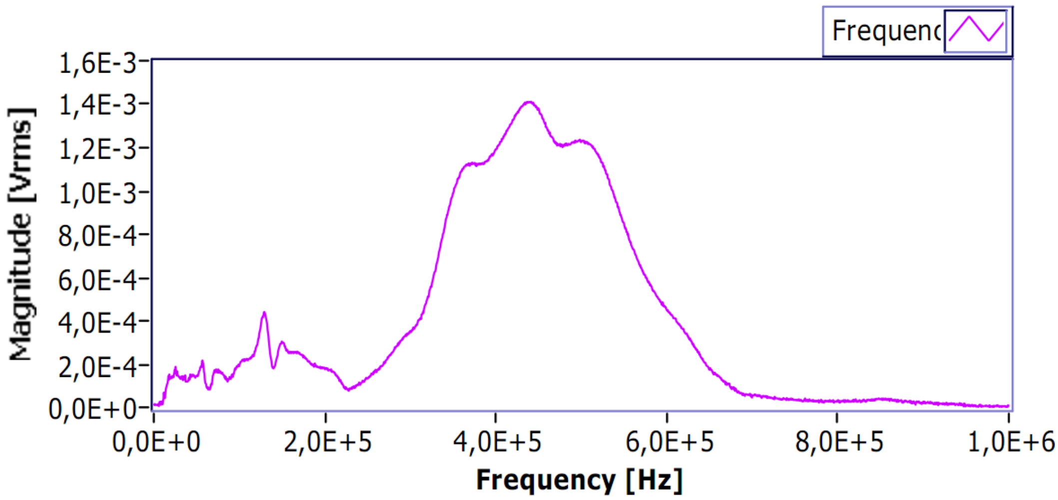


Figure C.3 Emitted US pulse by the sender of Freshcon device

C.3 Received signal

Before continuing with further explanation, it is necessary to determine two different time scales in an US test:

- The age of the concrete or mortar (Tc): It is the time in minutes or hours after the addition of water in the cementitous mixture. In this research program US tests last

48 h (2880 minutes) and a signal *(1)* is registered every minute *(2).* In this work due to the analyzed mixtures' composition, mortar with an age lower than 6 or 8 hours, it is considered young mortar, and with a higher age it is considered old mortar.

- The time scale for a registered signal (Ts): It is the time scale in one individual ultrasonic signal in micro- or milliseconds. Parameters of this time scale are set in Freshcon configuration. Typically, every signal has 16384 time samples in total, and 1638 of them are before time counter. There is a time of 0.1 µs between consecutive samples. It means that the time scale ranges from -163.8 µs to 1474.5µs with a sampling period of 0.1 µs.

As it has been mentioned before, setting and hardening of cementitous mixtures can be studied using US techniques based in the observation of waves transmitted through the mixtures. The registered signal's waveform, travel time, amplitude and frequency content are influenced by the elastic properties of the material. For a fly ash-based Self-Compacting Mortar (SCM) such as C1-S2-070-F3-075 *(3). Figure C.4* and *Figure C.5* show the evolution of the frequency content and amplitude of the signals recorded in a 48 hours US test. *Figure C.4* shows the raw signal's frequency spectrum and it can be noticed that most part of the emitted signal does not travel through the with low Tc, and after 2 days of test the frequency spectrum fits logically with the frequency content of the sent signal. *Figure C.5* shows the normalized frequency spectrum of the signals recorded for the same US test. For each signal, the normalized signal is calculated dividing the whole frequency spectrum by the maximum amplitude of the spectrum. In the first 300 minutes the signals are quite blurry and noisy. Then the maximum frequency peak grows from 20 kHz until 450 kHz. A hardening mortar sample can be considered like a low pass filter whose cut-off frequency is growing during the formation's process of the mortar's microstructure.

(1) Every signal registered by Freshcon is the average of 3 individual signals sent within a second. If it is not said differently, the word signal means the signal composed by the average of 3 signals sent in one second

(2) Several time configurations can be performed, but the most typical and intuitive one is to send and register one signal every minute

(3) *C1-S2-070-F3-075 SCM composed by normed sand, cement CBR CEM I 52.5N, water, fly ash and superplasticiser Glenium 51 with the following rates: S/C=3, W/C=0.45, C/P=0.75 and SP=0.7%*

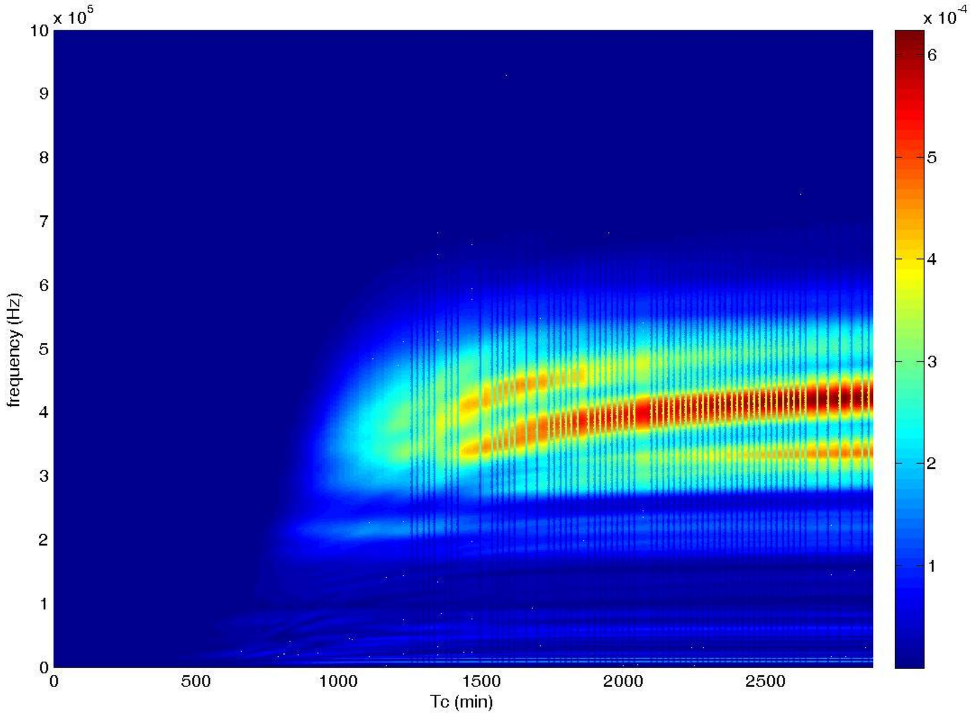


Figure C.4 Frequency spectrum of the signals registered during an US test for mixture C1-S2-070-F3-075

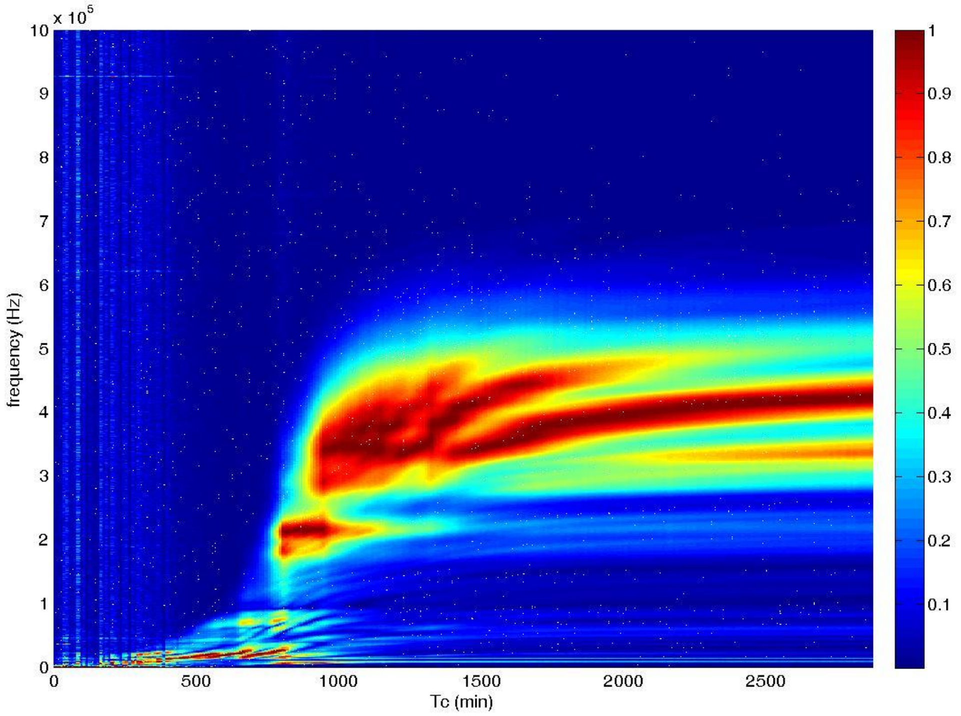


Figure C.5 Normalized frequency spectrum of the signals registered during an US test for mixture C1-S2-070-F3-075

A typically registered signal has different constitutive elements:

- The US received signal: it is the sent US signal after going through the cementitous sample. Its amplitude, transit time and frequency content depend on the analyzed mixture and its age.
- The trigger: the pulse which activates the piezoelectric sender is also registered and sets the time counter of the signal. It is a constant pulse located always close after time counter.
- Noise: High and low frequency noise detected by the receiver surface. It has approximately the same amplitude during the whole US test, and a constant random distribution all over the frequency spectrum, as showed in *Figure C.6.*

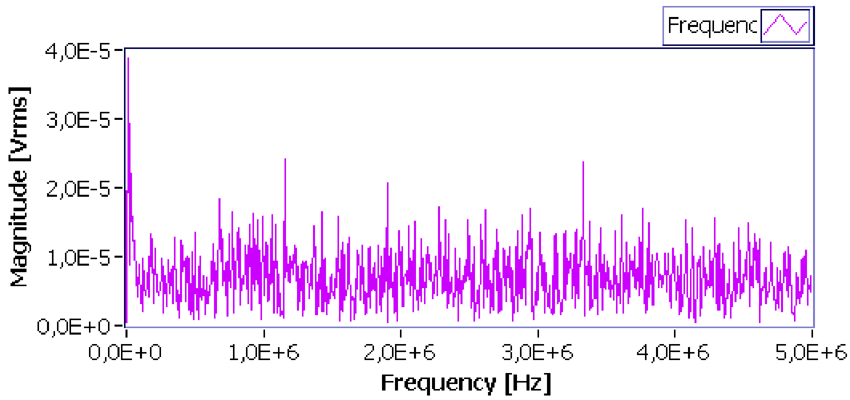


Figure C.6 Frequency spectrum of the noise found in the buffer of a signal

- Reflections: A part of the US signal is reflected by the receiver and it is registered later in first, second or third reflections.
- Onset time: time between the time counter and the arrival of the signal. It contains the calibration time and the signal's calibrated onset time, as it is showed in *Figure C.8*.
- Calibration time: Time between time counter established by Freshcon and the real time counter obtained from the calibration procedure.
- Calibrated onset time: Time between the real time counter and the arrival of the signal

A typically registered signal has three different parts, as it is showed in *Figure C.7*:

- Buffer: Samples stored before the time counter sample containing noise
- Main part of the signal: Main part which contains the trigger the US received signal, the trigger, the onset time and noise
- Rest of the recorded signal: Part of signal containing mainly reflections of the US received signal and noise.

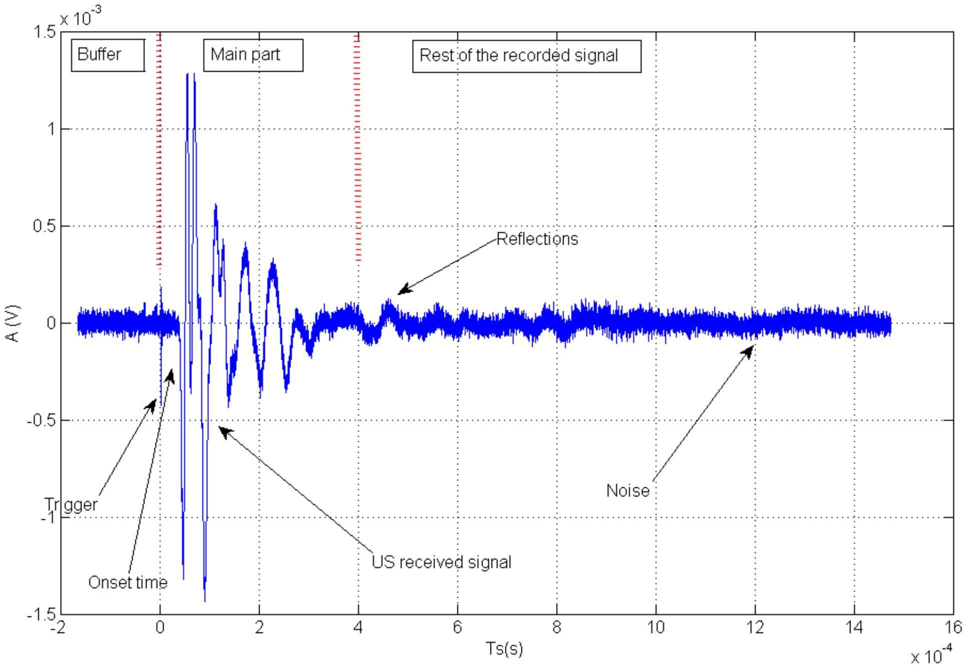


Figure C.7 Received signal at Tc = 600 min in SCM C1-S2-070-F3-075

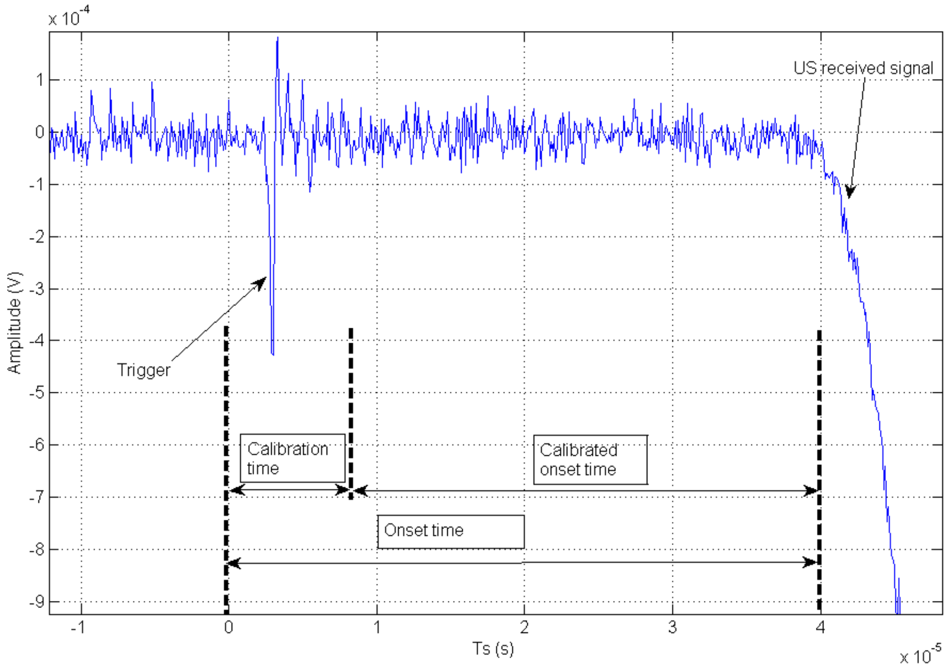


Figure C.8 Onset time in a signal at Tc = 600 min in SCM C1-S2-070-F3-075

Frequency spectrum figures show that the shape and the amplitude of signals along the test change drastically. Four signals registered after 10, 200, 500 and 1500 minutes (Tc) after the start of the US test are used to illustrate these changes. At Tc=10 min (*Figure C.9*) the registered signal is very noisy. The US signal is much smaller than the noise and the trigger. A manual determination of the onset time is impossible to perform. At Tc=200 min (*Figure C.10*) the signal continues being noisy, but the US pulse begins to be seen with some troubles. An arrival time of the signal can be determined but the resolution is very low and the error due to such a noisy signal is big. At Tc=500 min (*Figure C.11*) the signal can be distinguish form the noise. While the trigger amplitude and the noise level don't change, the amplitude of the received US pulse has increased considerably. Thus, an arrival time can be determined with a good resolution, but the noise is big enough to influence this arrival time. The trigger signal amplitude is more or less as big as the US pulse amplitude. At Tc=1500 min (*Figure C.12*) the received US signal amplitude is much bigger than the noise and the trigger and the noise has a little or no influence in the US pulse velocity determination. It should be noticed that the vertical axe changes in *Figure C.12.*

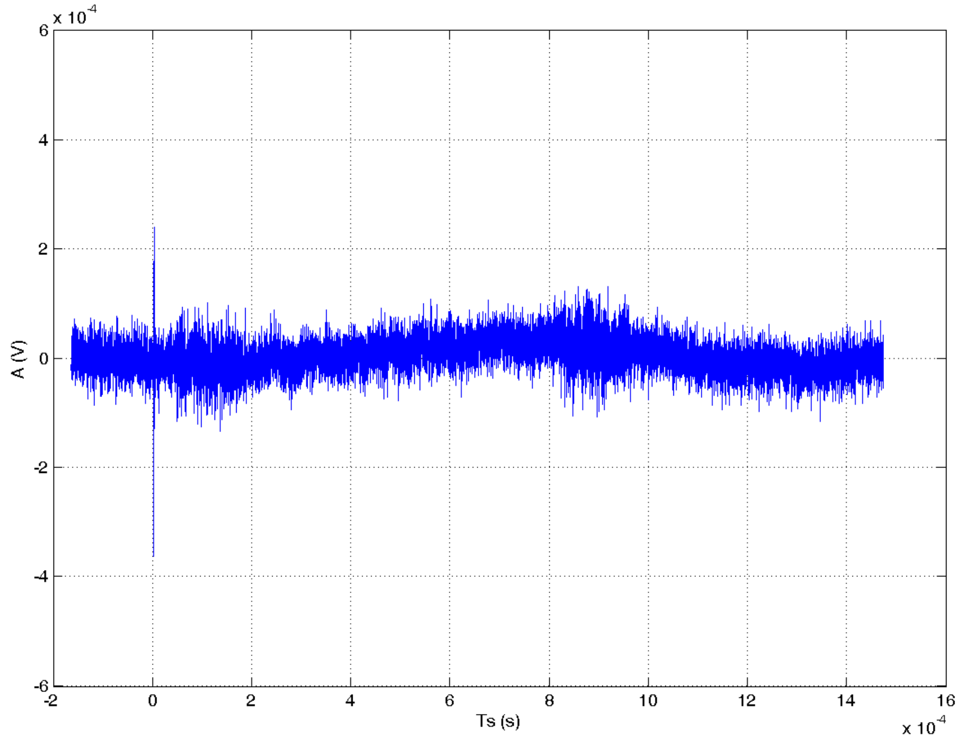


Figure C.9 Received signal at Tc=10 min for SCM C1-S2-070-F3-075

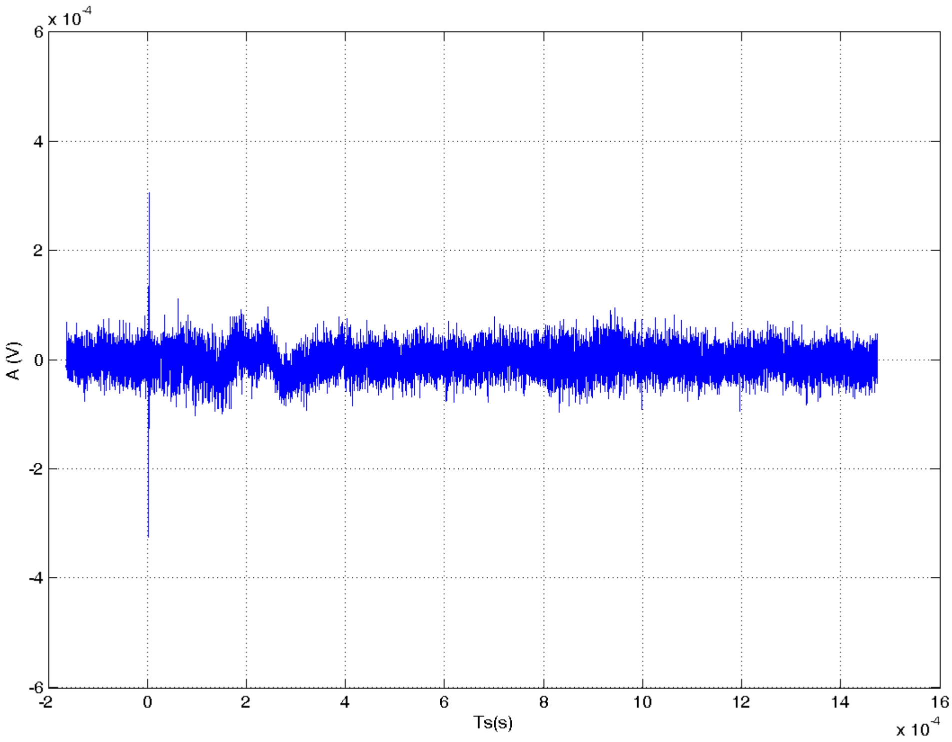


Figure C.10 Received signal at Tc=200 min for SCM C1-S2-070-F3-075

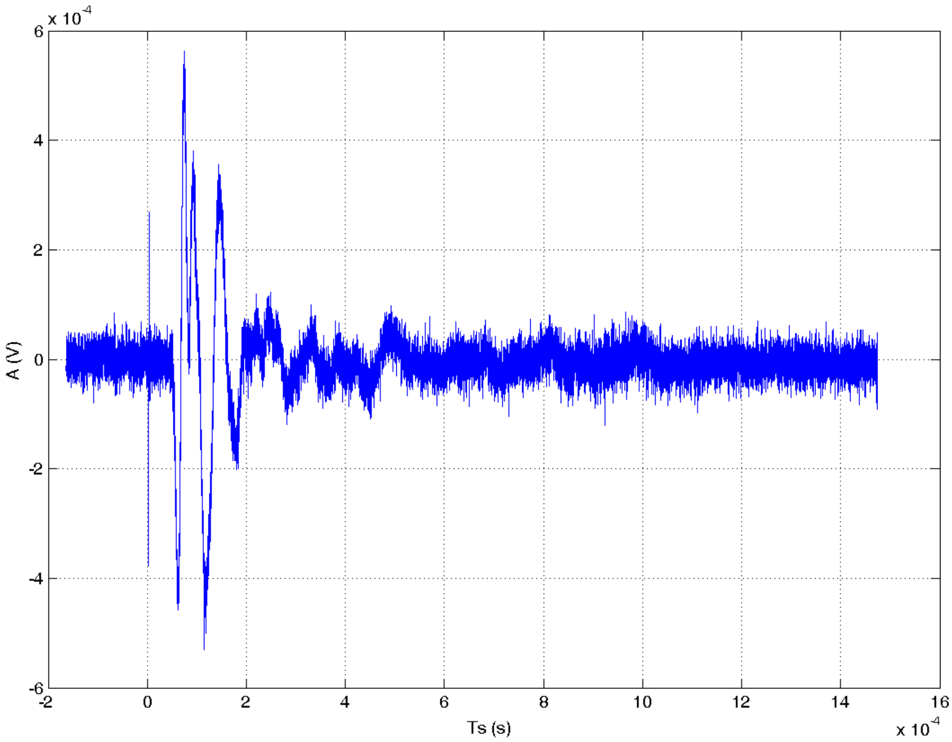


Figure C.11 Received signal at Tc=500 min for SCM C1-S2-070-F3-075

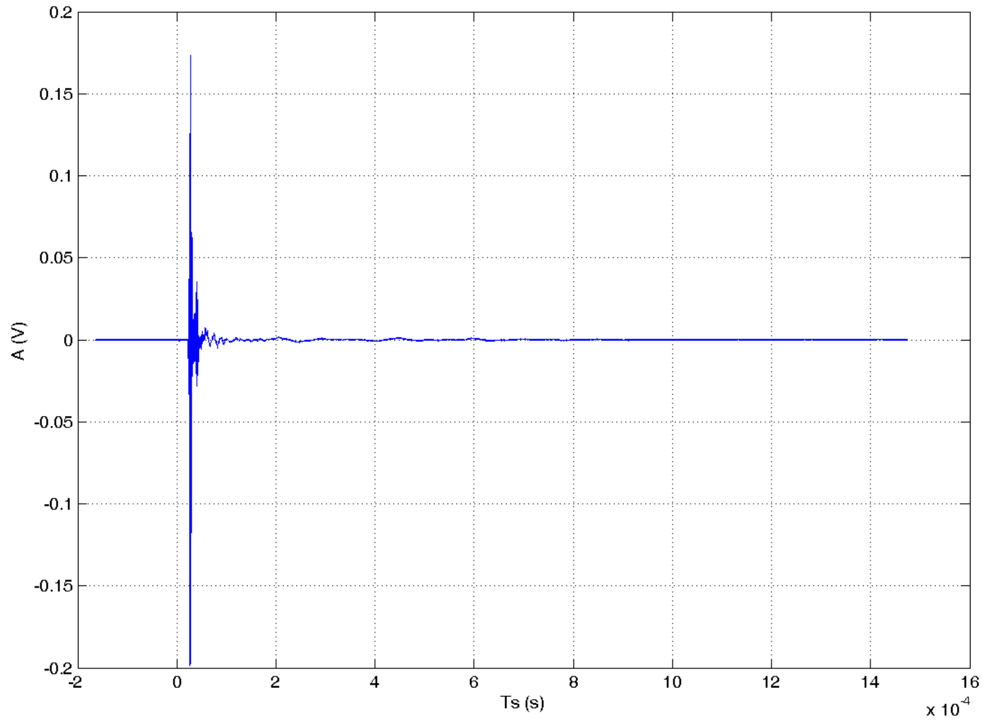


Figure C.12 Received signal at Tc=1500 min for SCM C1-S2-070-F3-075

C.4 Determination of the US signal's onset time

C.4.1 Introduction

The determination of the onset time of a transient signal is an important task in many fields of science. Seismology and acoustic emission measurement are related fields which use the phenomenon of stored elastic energy being released as elastic waves due to sudden fracturing in a rigid body. The onset time is usually picked as the point where the difference from the noise occurs first, although an experienced analyst will often extrapolate slightly back into the noise. The simplest form for onset picking is to use an amplitude threshold-picker. However, small amplitude signals and/or signals with a high noise levels are not valuable for a pure threshold approach. An autoregressive AIC-picker produces reliable results for acoustic emissions and for ultrasound signals with a relative high success rate. The problem concerning acoustic emissions and ultrasound signals in concrete is that signal and noise are often in the same frequency range. Furthermore, as it was explained before, the signal to noise ratio of acoustic emissions is generally not constant during an experiment.

C.4.2 Wavelet transform

An autoregressive AIC-picker gives picks (picks means determined onset times) of higher quality if the AIC is only applied to a part of the signal which contains the onset, of course. Therefore, the onset is prearranged by using the Hilbert transform. The transform leads to a certain envelope of the signal. The Hilbert transform $\overline{R}(t)$ of a real time dependent function R(t) is defined as:

$$\overline{R}(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{R(u)}{t-u}du = H\{R(t)\}$$

where t denotes the time and the singularity at u=t is handled by taking the Cauchy principle value of the integral. The Hilbert transform is represented by a convolution integral, i.e. the Hilbert transform is a causal transfer function which behaves like a filter. Transforming a time series by the Hilbert transform, a phase shift of π/2 is generated. Thus, the envelope time function E(t) can be calculated in the following way:

$$E(t) = \sqrt{R(t)^2 + \overline{R}(t)^2}$$

The envelope is then used for prearranging the onset by a simple threshold. Each envelope is squared and normed, that a constant threshold value can be applied to all signals, as it is showed in *Figure C.13*. A window of several hundred samples e.g. 400 before and 150 after this points then cut off the signal. Within this signal the onset is determined exactly using the AIC.

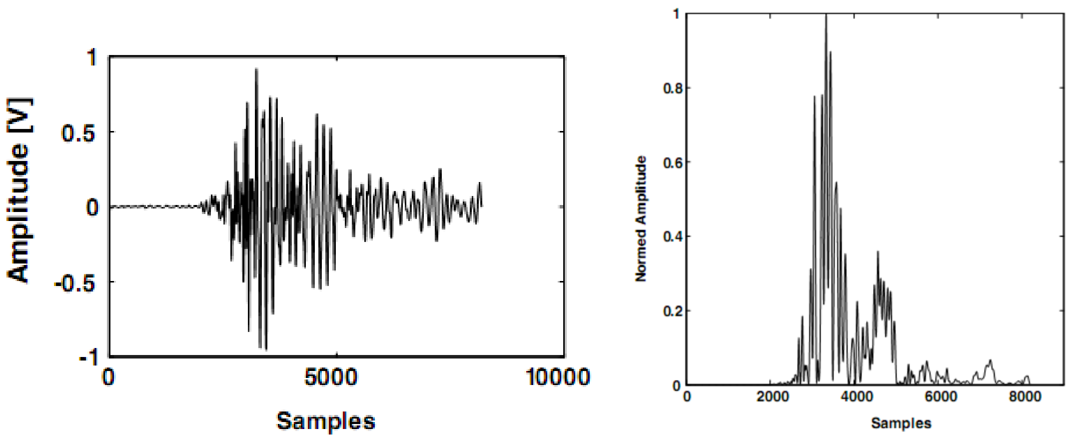


Figure C.13 Signal and its normed envelope (Source:[12])

C.4.3 AIC picker

The exact onset is determined by calculating the AIC function direct from the signal:

$$AIC(t_w) = t_w \log(var(R_w(t_w,1))) + (T_w - t_w - 1) \log(var(R_w(1+t_w, T_w)))$$

The index w e.g. from R_w denotes that not the whole time series is taken but only the chosen window containing the onset. T_w is the last sample of the curtate time series, t_w ranges through all samples of R_w and var denotes the variance function. The term $R_w(t_w,1)$ means that the variance function is only calculated for the samples between the first one and the current value of t_w, while $R_w(1+t_w, T_w)$ means that all samples ranging from $1+t_w$ to T_w are taken. The global minimum of the AIC function defines the onset point of the signal, as it is showed in *Figure C.14* [12].

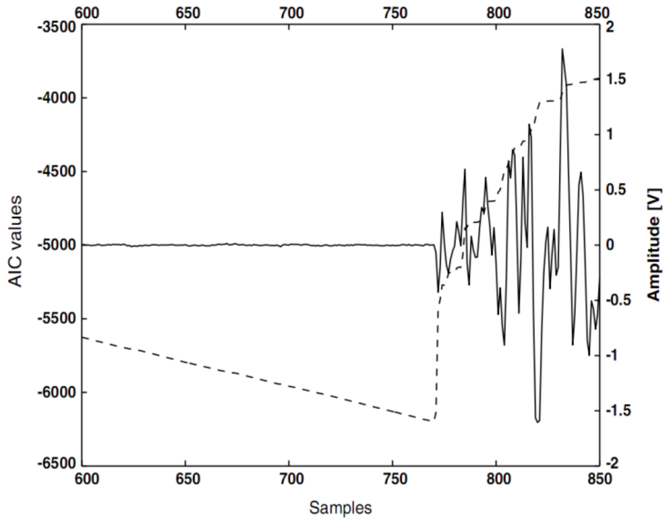


Figure C.14 Signal and its AIC function (Source:[12])

C.5 Starting point: Determination of raw signal's onset time with AIC picker algorithm

For a mixture C1-S2-040-F3-075 *(4)* a reference curve has been created using manual picking in an original signal, measuring the possible error introduced by the user. Since calculating a manual onset time is a long and tedious work, one signal every 20 minutes is selected before Tc=900 minutes, and after Tc=900 minutes one every 30 minutes. The maximum error is the width of a pulse flank measured in number of time samples (Ts) as it is shown in *Figure C.15*. It means that the reference curve is not a curve but a surface in which the US pulse velocity should be located with a width of twice the width of a pulse flank in samples. The younger the mixture is, the bigger the width of the flank is and the precision in the manual picking decreases. A velocity curve using the AIC picker algorithm is created, in order to check the reliability of AIC picker algorithm using the original signals.

(4) C1-S2-040-F3-075 SCM composed by normed sand, cement CBR CEM I 52.5N, water, fly ash and superplasticiser Glenium 51 with the following rates: S/C=3, W/C=0.45, C/P=0.75 and SP=0.4%

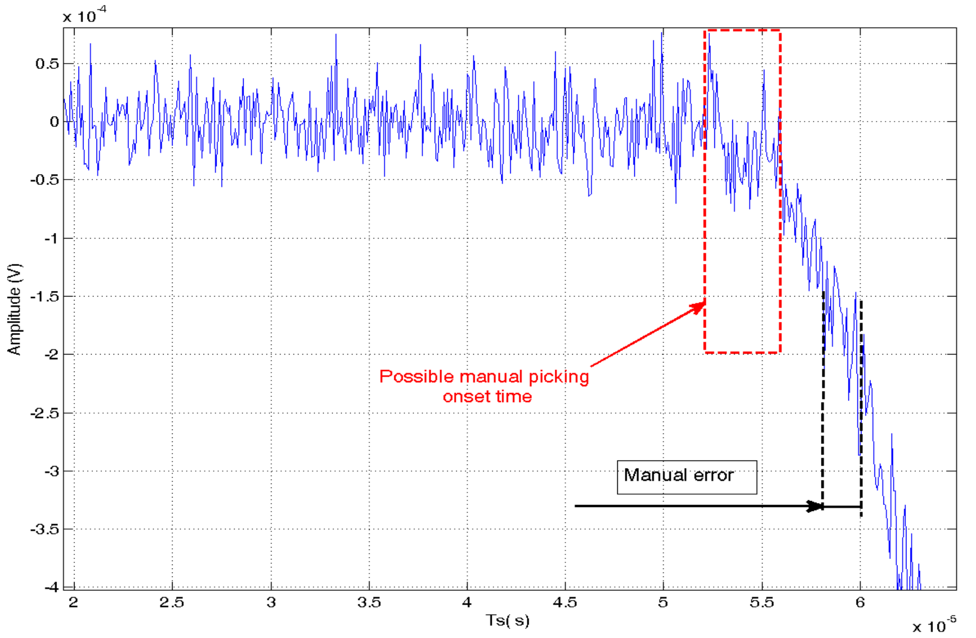


Figure C.15 Manual picking onset time at Tc = 450 min

Figure C.16 shows that the velocity values calculated with AIC picker are generally lower than expected, and that AIC picker doesn't work with signals younger than 400 minutes. It means that in a time close to the maximum gradient time, and the initial setting time of this mixture, very important parameters in an US test, the AIC picker can't give any velocity result. All these problems have mainly two causes: a trigger amplitude similar or bigger than the US received signal, and the delay in the onset time determination with AIC picker caused by the noise.

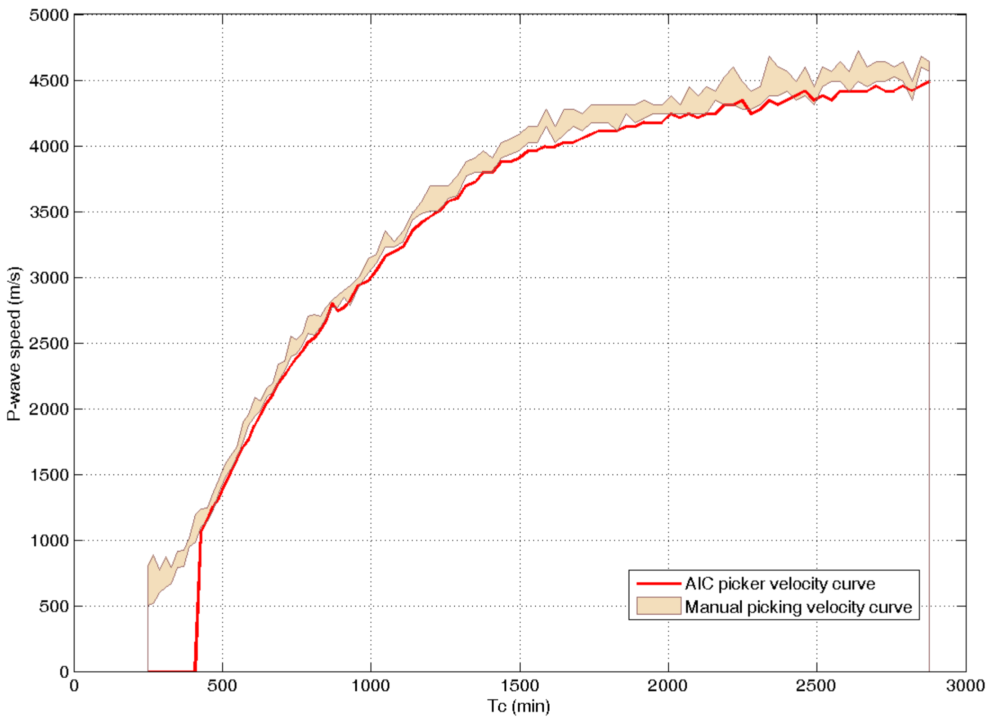


Figure C.16 Velocity curves with AIC picker algorithm and with manual picking from original data

An error expressed in terms of velocity is not a good indicator of the error committed in the detection of the onset time the received US signal. While by speeds of 300 m/s with a distance of 55 mm between transducers a delay in the onset time's detection leads to a decrease in the velocity of 0.2 m/s, by speeds of 5000 m/s the same delay leads to a diminution of 55 m/s. Therefore the reference curve with Tc lower than 500 minutes (as *Figure C.17* shows) is not accurate enough to assure that, if one calculated velocity value is located in the surface of the manual picking velocity curve, this value is a correct one.

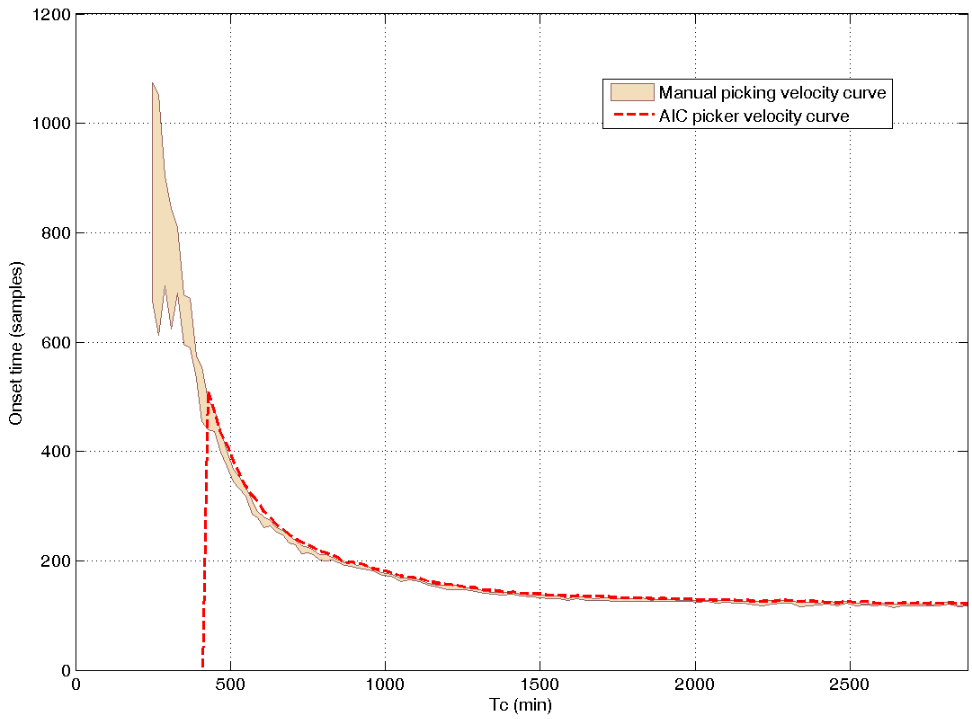


Figure C.17 Onset time with AIC picker algorithm and with manual picking from original data

In the following pages, the problems which lead to this inaccurate AIC picker velocity curve are described in detail.

C.6 Trigger problems

If the trigger amplitude has the same order of magnitude than the US received signal, the preliminary onset time is detected with the trigger signal and not with the real US signal (*Figure C.18*). Therefore the AIC picker doesn't work in the zone where the real signal arrives, so it can't obtain a good result. That is the reason why the AIC picker algorithm does not give any velocity result in young mixtures, when the trigger amplitude is similar or higher than the US received signal.

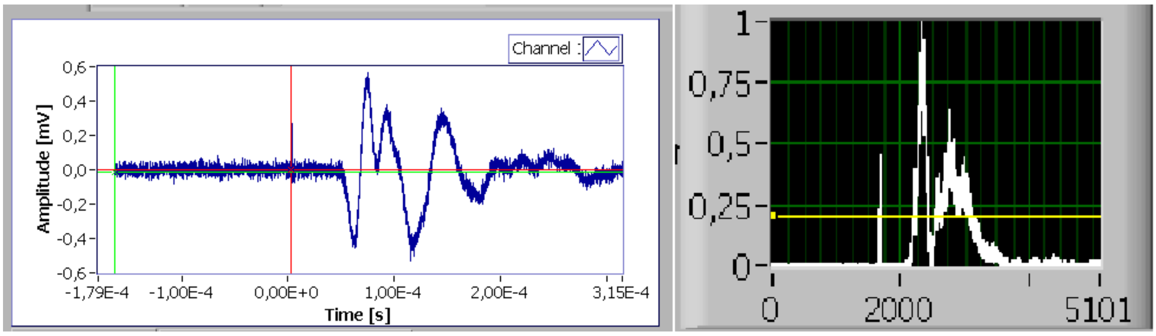


Figure C.18 High amplitude trigger causing a wrong onset time

C.7 Noise/signal rate problems

The detection of the arrival time is influenced by the noise contained in the signal. In order to check this influence, different noise levels are added to a synthetic sinusoidal signal with a known arrival time of 500 time samples and its AIC function is calculated (*Figure C.19*). It is observed that when the noise level increases, the error in the onset time detection increases too. In *Figure C.20* and *Figure C.21*, it is seen that a noise/signal rate value of 1 (*Figure C.22*) is the limit in this case to achieve a good result. If this rate is higher, the detection of the arrival time of the signal is strongly influenced by the noise, detecting sometimes the signal before it arrives, fact that shows that the AIC picker is not a good choice for noisy signals. For a real signal, the first flank of the arrival signal is not as steep as in this example, the first semi-period of the signal is more damped and the frequency spectrum of the signal is more complex. Consequently, the error in AIC picker algorithm is bigger. But the main conclusion from this example is that the noise/signal rate should be as low as possible, to perform a good onset time determination using AIC picker.

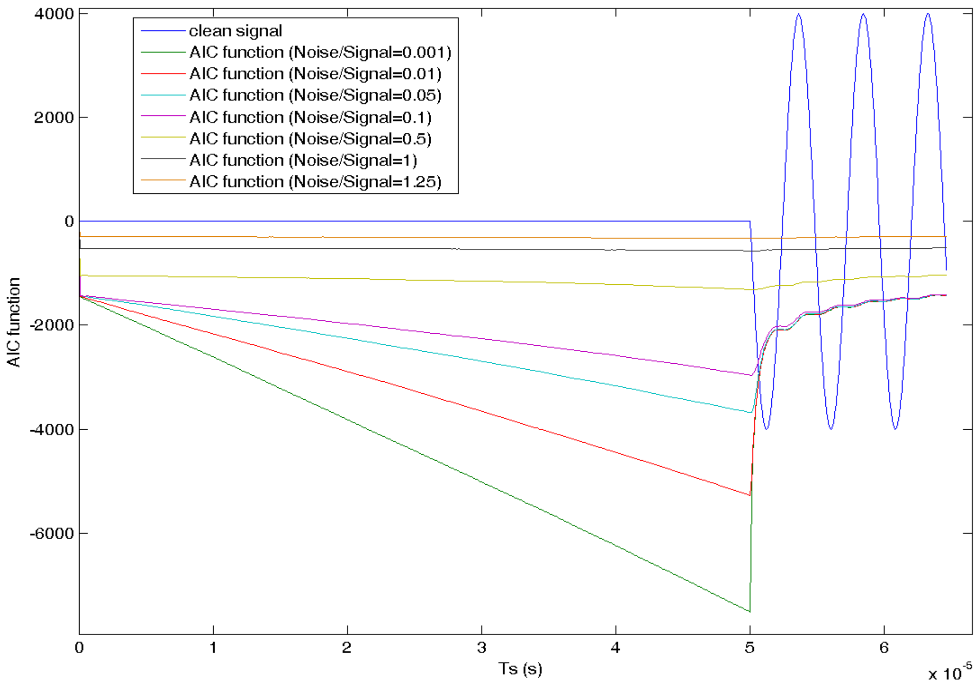


Figure C.19 AIC function of a synthetic function with different noise levels

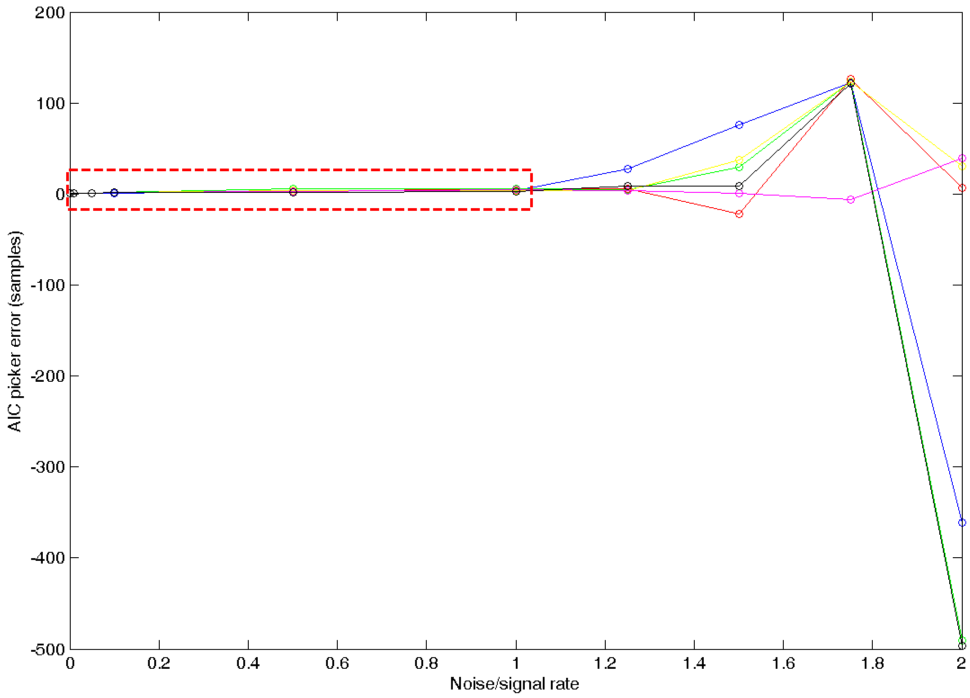


Figure C.20 Possible AIC picker errors for different noise signal rates

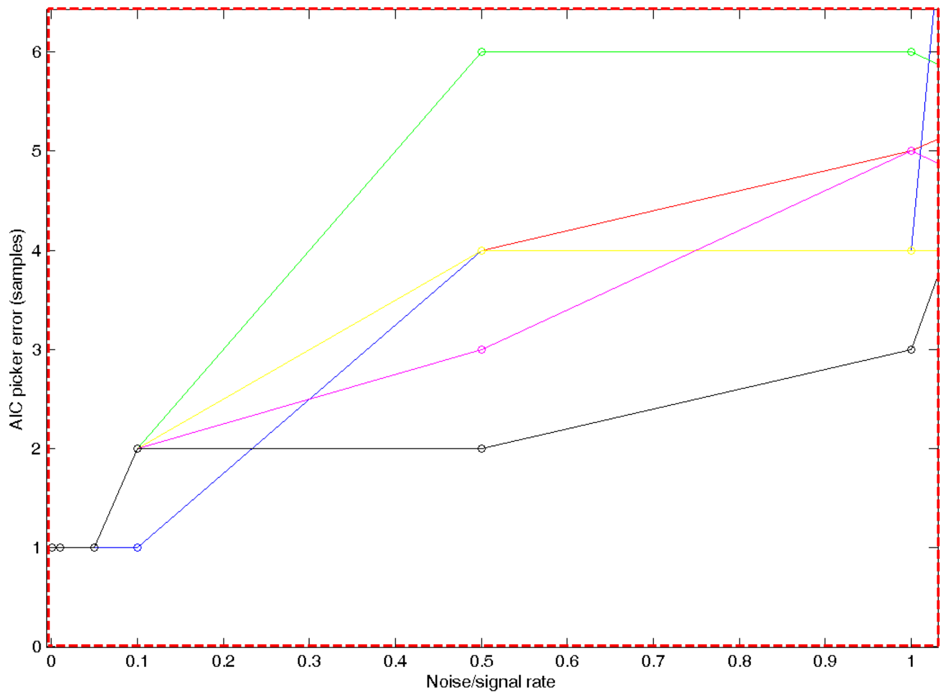


Figure C.21 Zoom of possible AIC picker errors for different noise signal rates

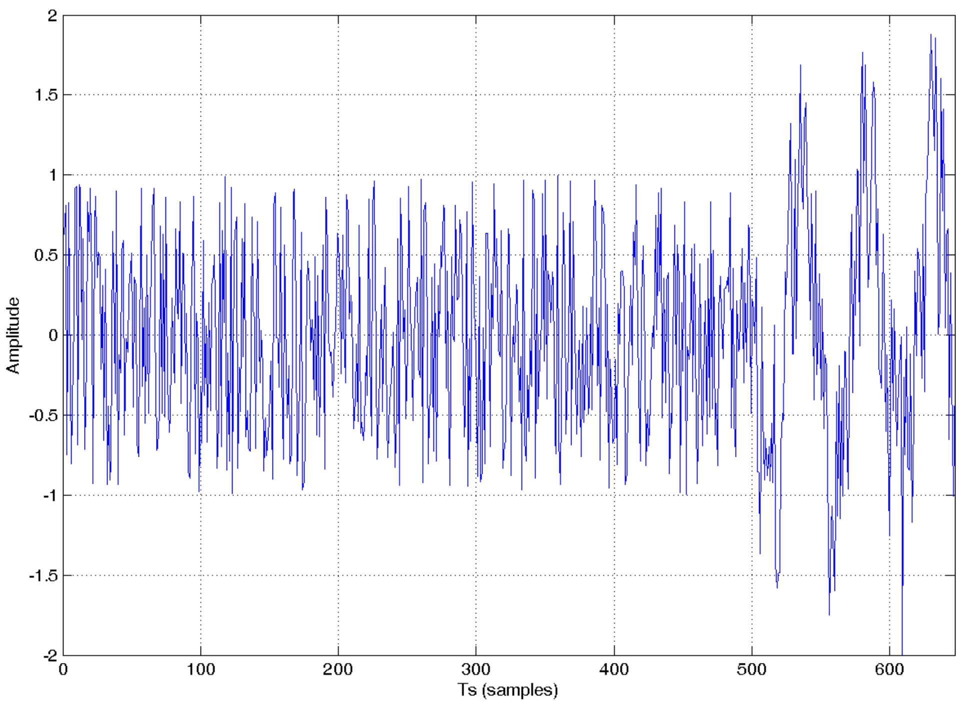


Figure C.22 Synthetic signal with a noise/signal rate of 1

C.8 Other problems

Another two minor inconveniences were detected in the use of AIC picker algorithm:

- The parts of the signal registered before time 0 sample (buffer) and after Ts=0.5ms only contain noise. It is preferable to eliminate these parts to accelerate the application.
- Spurious high amplitude peaks at the end of the signal can produce a maximum in the normalized wavelet used to obtain the preliminary onset, as it is showed in *Figure C.23.* So, the preliminary onset is set at the end of the signal, and it leads to a wrong calculation of the arrival time.

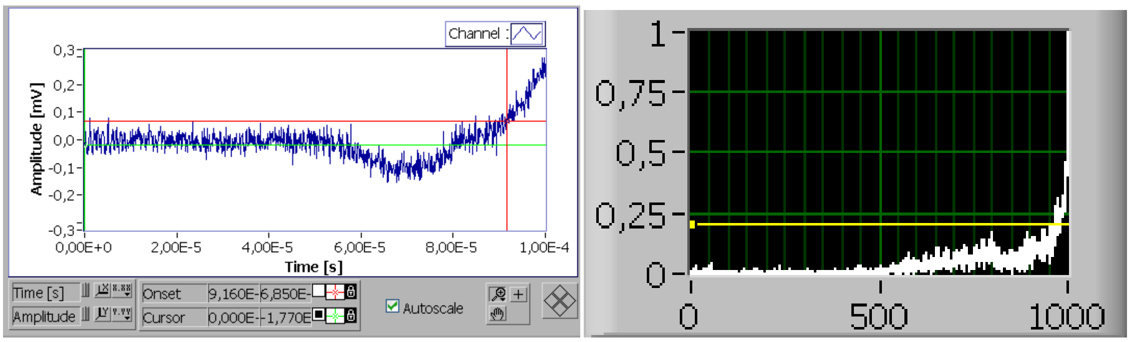


Figure C.23 Example of a high amplitude peak at the end of a signal

Anexo D

D. Automatized method for the Freshcon data treatment

D.1 General description

An automatized method has been developed to obtain velocity curves from US test data, which solves or minimizes as much as possible the problems described in the precedent chapter. The method is based on filtering original or composed signals with a discrete Bessel filter. In young mixtures, a signal is composed by calculating the average of several consecutive signals in order to reduce the noise by compensation. In older mixtures single raw signals are filtered. During the whole process, it was tried to preserve the original shape of the US received signal, while the troublesome elements such as the trigger and noise were modified. The main objective is to approach the resultant velocity curve with the manual picking velocity curve.

The method has 7 main steps, as the schedule in *Figure D.1* shows :

1. From the frequency spectrum of all the raw signals a cut-off frequency curve is calculated in function of Tc. With this cut-off frequency calculation it is also determined which signals are going to be composed by calculating the average of several signals and which ones not, and the number of signals to calculate the average signal.
2. If necessary, the average signal of several original signals is calculated
3. The signals are filtered with a discrete Bessel filter. The main function of the filter is to attenuate the noise level in the received signal in order to allow a better work of the AIC picker algorithm.
4. By means of the cross correlation function the delay between the pre-filtered and the filtered signals is calculated
5. The part of the signal containing the trigger, the onset time and the US received signal is modified to improve the performance of the AIC picker and the rest of the signal is not considered any more.
6. After having treated all the signals the onset time of the signals is detected and a preliminary velocity curve is obtained by means of AIC picker algorithm implemented in Freshcon offline
7. At the end the preliminary velocity curve is corrected: the filter delay is subtracted to the calculated onset time and the velocity is modified considering the real distance between transducers and not the Freshcon default one.

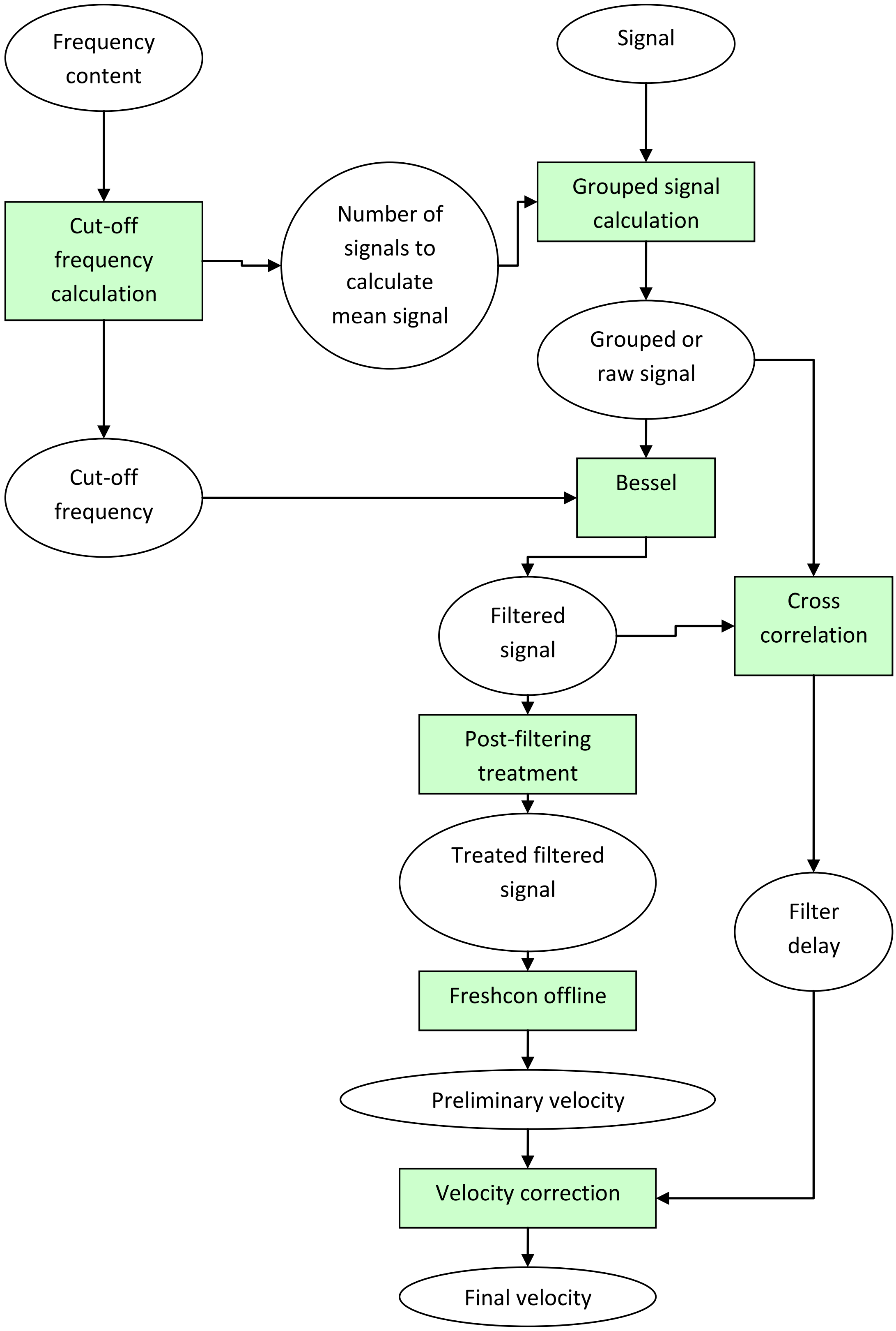


Figure D.1 General schema of the Freshcon data treatment

D.2 Cut-off frequency calculation

From the frequency spectrum of all the raw signals the Bessel filter's cut-off frequency curve is calculated in function of Tc. These cut-off frequency values have a major importance in the efficiency of the method: cut-off frequency values which are to high produce too noisy signals which complicate the AIC picker labour, while too low values modify too much the shape of the received signal, especially the high frequency content, which produces steeper signal flanks.

The filter's cut-off frequency is calculated in steps (*Figure D.2*):

1. The frequency spectrum is divided by the maximum amplitude of the spectrum (normalization)
2. The normalized frequency spectrum is compared with a threshold (TH). The maximum frequency with amplitude bigger than TH is selected.
3. The selected frequency is multiplied by a security factor (CS) to obtain the desired cut-off frequency

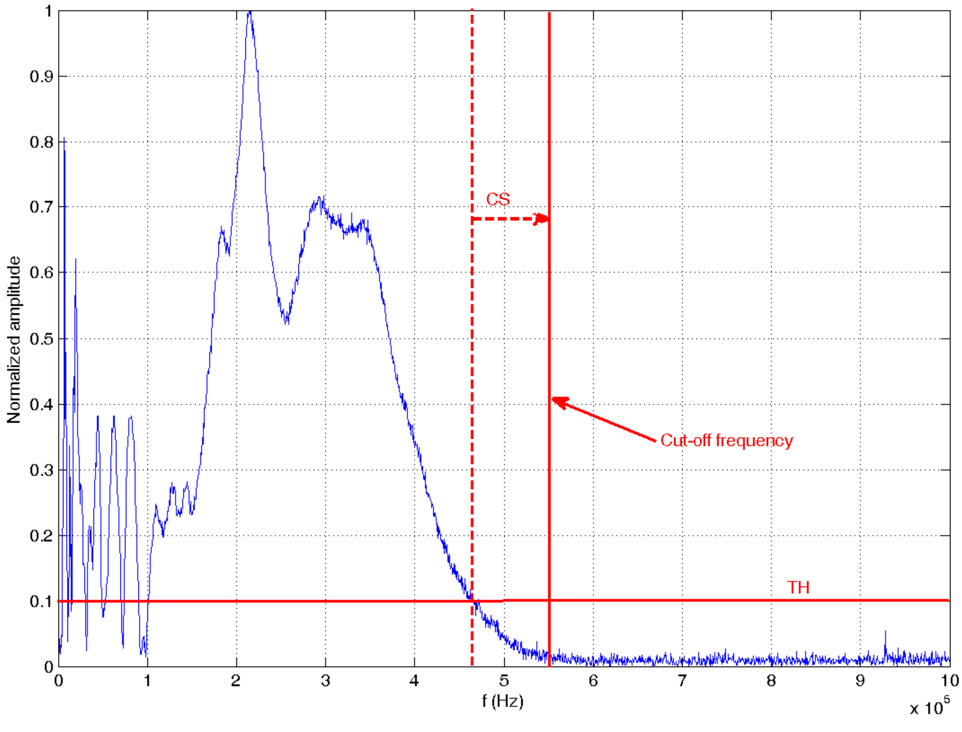


Figure D.2 Normalized frequency spectrum and filter's cut-off frequency calculation for a signal at Tc=900 min in SCM C1-S2-070-F3-075

In order to calculate an appropriate filter's cut-off frequency, it is very important to determine adequate values for the parameters TH and CS. As a general consideration, in a US signal with very low noise levels, TH and CS should be as small as possible, and so, the cut-off frequency would fit better with the frequency spectrum. Appropriate values for TH and CS can vary from one mixture to another one. In the following paragraphs it is going to be described how to calculate them, through one example of SCM such as C1-S2-070-F3-075. Four different thresholds (TH=0.05 (*Figure D.3*), 0.1 (*Figure D.4*), 0.15 (*Figure D.5*) and 0.2 (*Figure D.6*)) are checked. TH=5 is not very useful because it doesn't give any acceptable result for mixtures younger than 500 minutes in this example, because high frequency noise levels at this age are bigger than 5% of the maximum of the signal. For the other three TH values, there isn't enough evidence yet to make a well-considered selection.

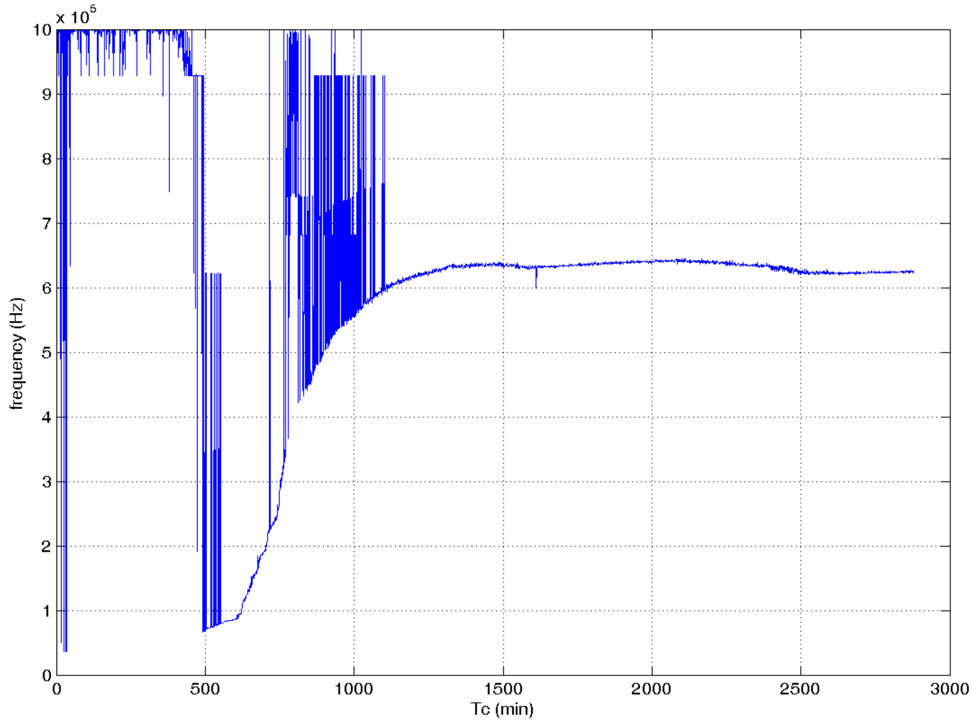


Figure D.3 Maximum frequency at TH =0.05 for SCM C1-S2-070-F3-075

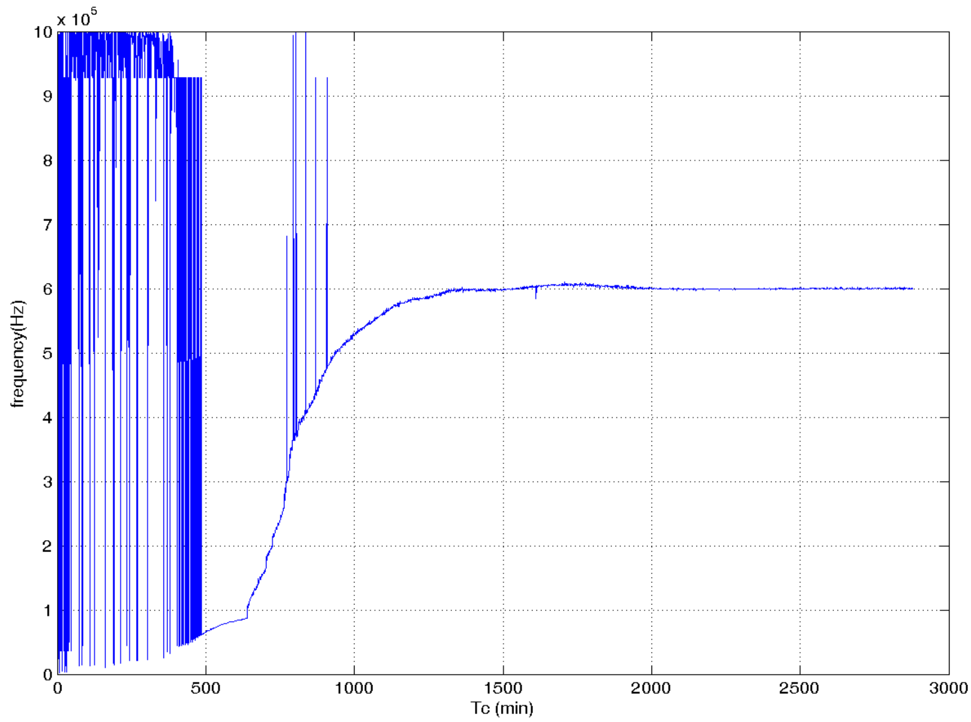


Figure D.4 Maximum frequency at TH =0.1 for SCM C1-S2-070-F3-075

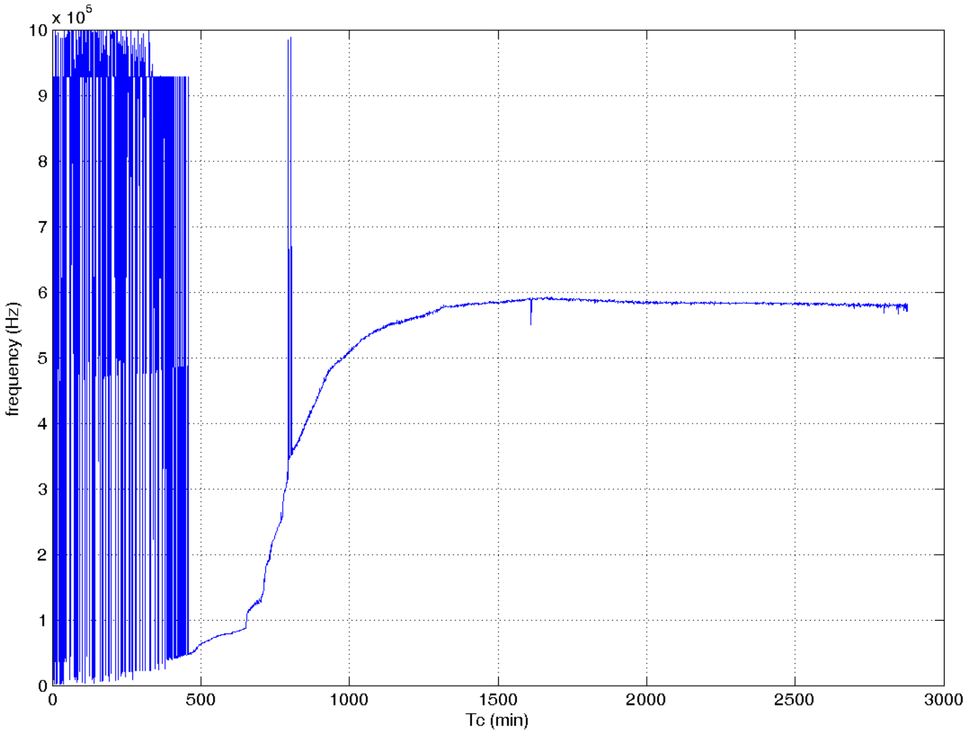


Figure D.5 Maximum frequency at TH =0.15 for SCM C1-S2-070-F3-075

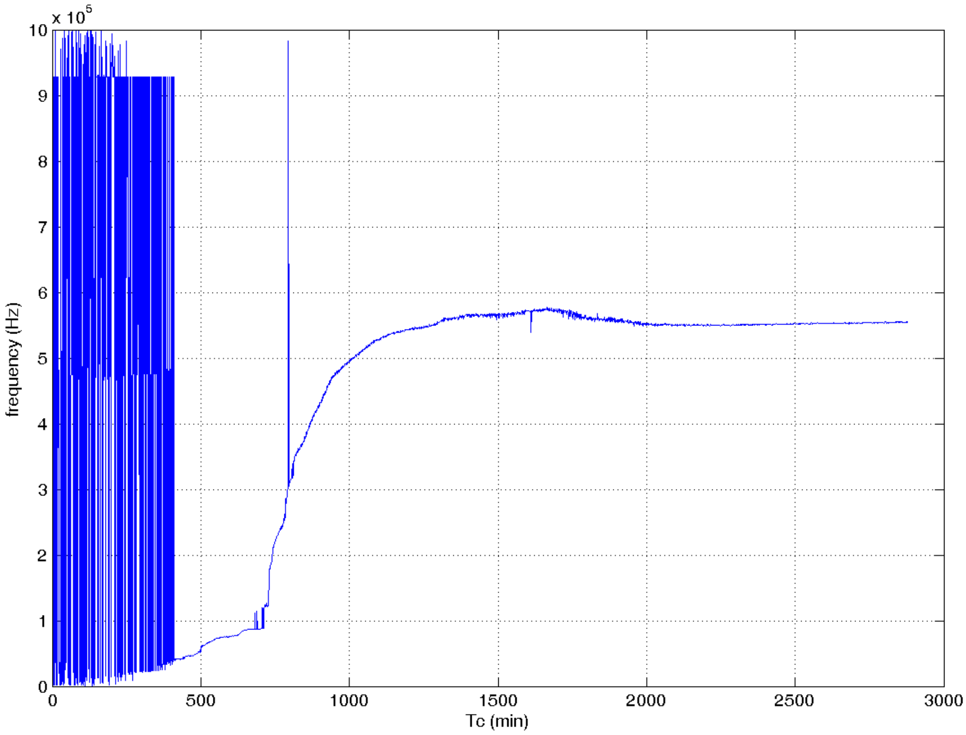


Figure D.6 Maximum frequency at TH =0.2 for SCM C1-S2-070-F3-075

High frequency noise levels bigger than TH leads to frequency values bigger than 700 KHz, which clearly cannot correspond to an upper limit of the US signal's frequency spectrum. Consequently, they are eliminated and replaced by a plausible cut-off frequency value. This plausible cut-off frequency value is determined in the following way, checking the cut-off frequency from high to low Tc, if one value is bigger than the cut-off frequency of the one minute older signal multiplied by a factor (AI), the value of the one minute older signal is set as filter's cut-off frequency. By default AI=1.2 allows gradual increases in the cut-off frequency curve going from older to younger concrete (which theoretically is not expected, but the real spectrum has irregularities), but it eliminates the peaks caused by high frequency noise levels. After eliminating the peaks in the cut-off frequency, it is possible to choose between TH= 0.1, 0.15, or 0.2. Because the US sent signal maximum frequency is around 700 kHz, three security factors (CS= 1.2, 1.25 and 1.3) are calculated to obtain a cut-off frequency of 720kHz after 2 days. Consequently three different cut-off frequencies curves are built, as it shows *Figure D.7*.

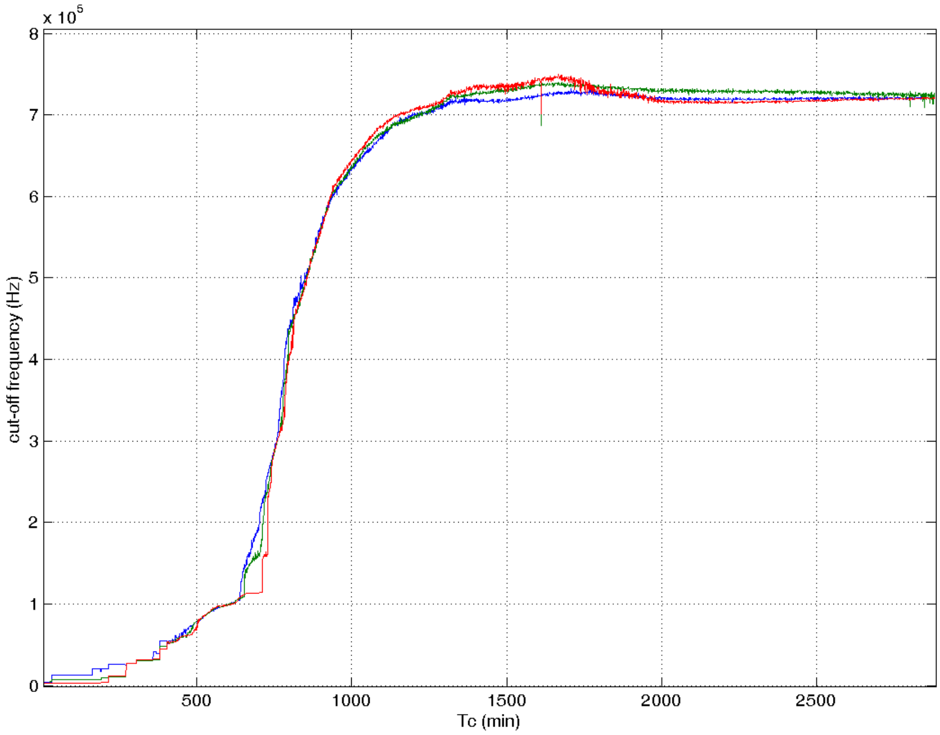


Figure D.7 Different cut-off frequency curves for TH= 0.1, 0.15 and 0.2

A value of TH=0.1 is preferable to the other two ones because of three reasons:

- After Tc=1500 min decreases in the cut-off frequency have no physical reason. They are caused by bigger amplitude in the US received signal which sets higher absolute amplitude as threshold and consequently a lower cut-off frequency, as it can be seen in *Figure C.4*. The TH=0.1 produces a more constant cut-off frequency, which corresponds to a constant US sent signal's frequency band, as *Figure C.5*.
- Around Tc= 700 min, there is a big difference between TH=0.1 and TH=0.2. While the increment in the cut-off frequency with TH=0.1 is more gradual for TH=0.15 and 0.2 it is much steeper. Steps and jumps in cut-off frequencies lead to jumps in p-wave

velocity curves, and there is no physical reason response of the US pulses to the microstructure development of the concrete to produce such steps.

- Before Tc=200 min noise and US signal have similar amplitude, so it is difficult to determine accurately a correct cut-off frequency. It is better to keep a high cut-off frequency calculated with older samples. The remaining noise can be filtered with the help of other methods.

So the parameters TH=0.1, CS=1.2 and AI=1.2 are set by default for the filter's cut-off frequency calculation. For very different mixtures these parameters could be invalid and the researcher should change them following the above described procedure. With these parameters a preliminary cut-off frequency is calculated. But the shape of this preliminary cut-off frequency is irregular, and it doesn't increase gradually but with some little jumps or steps. As *Figure D.8* shows, jumps in cut-off frequency curve cause discontinuities in velocity curves which modify the shape of the gradient of the curve. Therefore it is necessary to make the preliminary cut-off frequency curve smoother, for example, calculating for each value the mean with the 49 previous and 49 next velocity values (*Figure D.9*).

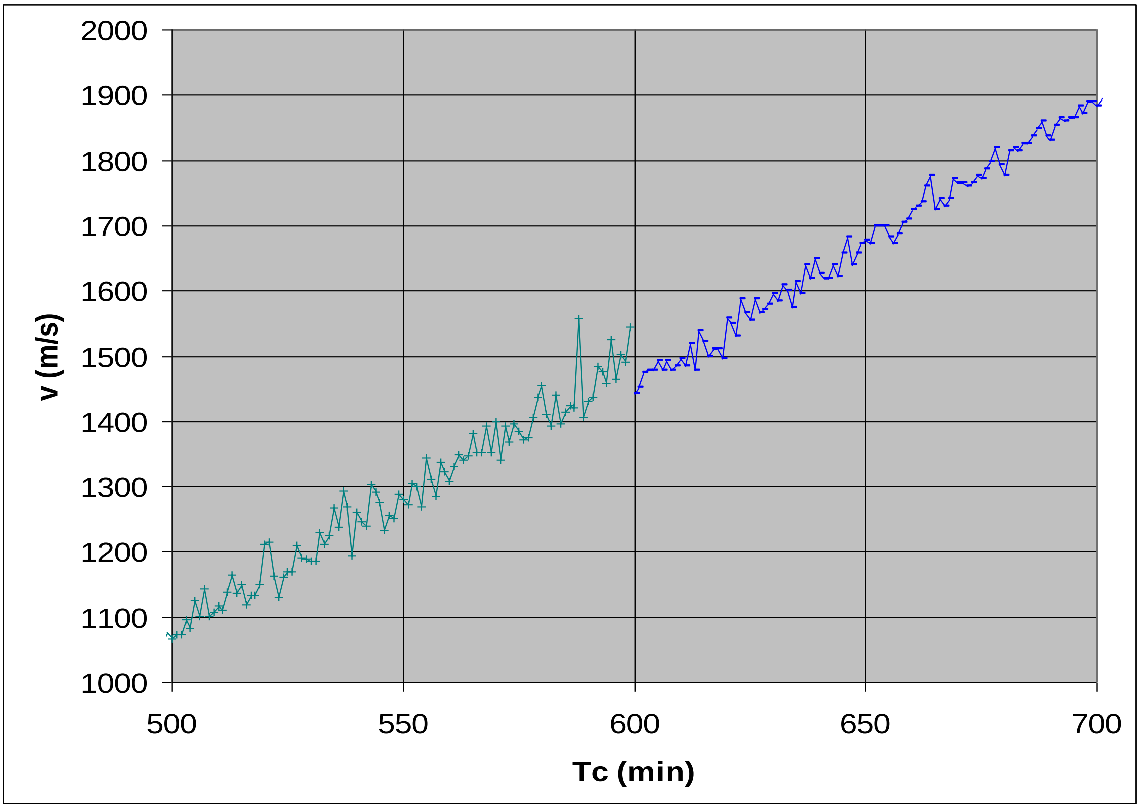


Figure D.8 Jump in velocity curve caused by different cut-off frequency levels: 300 kHz for Tc<600min and 600 kHz for Tc>600 min in SCM C1-S1-120-F3-075

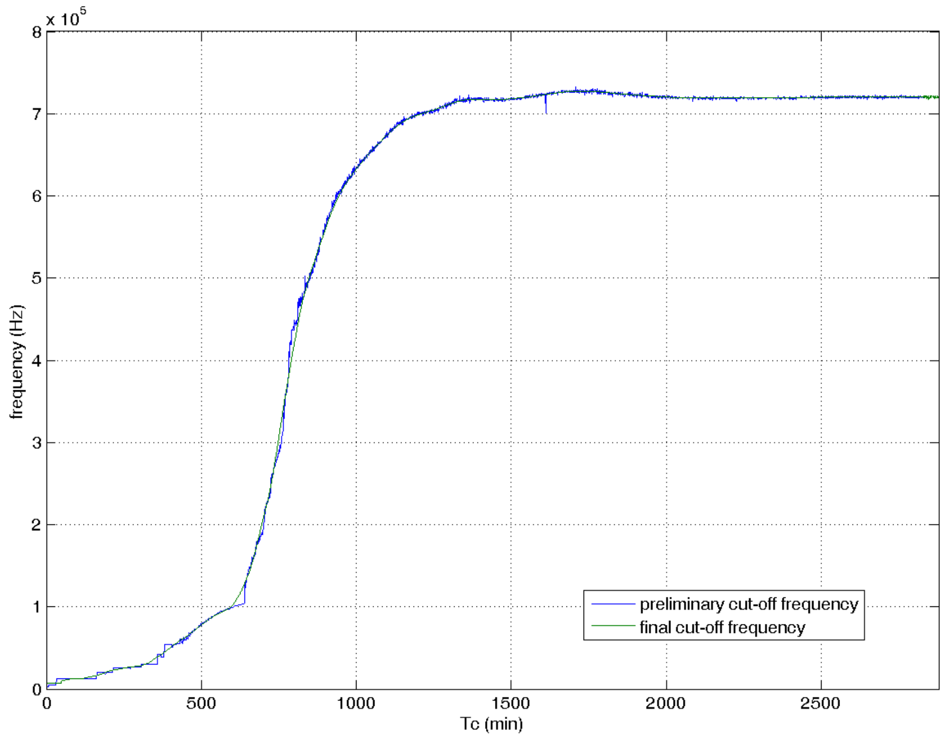


Figure D.9 Preliminary and final cut–off frequency for SCM C1-S2-070-F3-075

Figure D.10 gives a general view of the frequency spectrum of the received signal traveling through a mortar sample during 2 days, showing that the filter's cut-off frequency is always bigger than the signal content, and it changes progressively with the frequency content of the received signal.

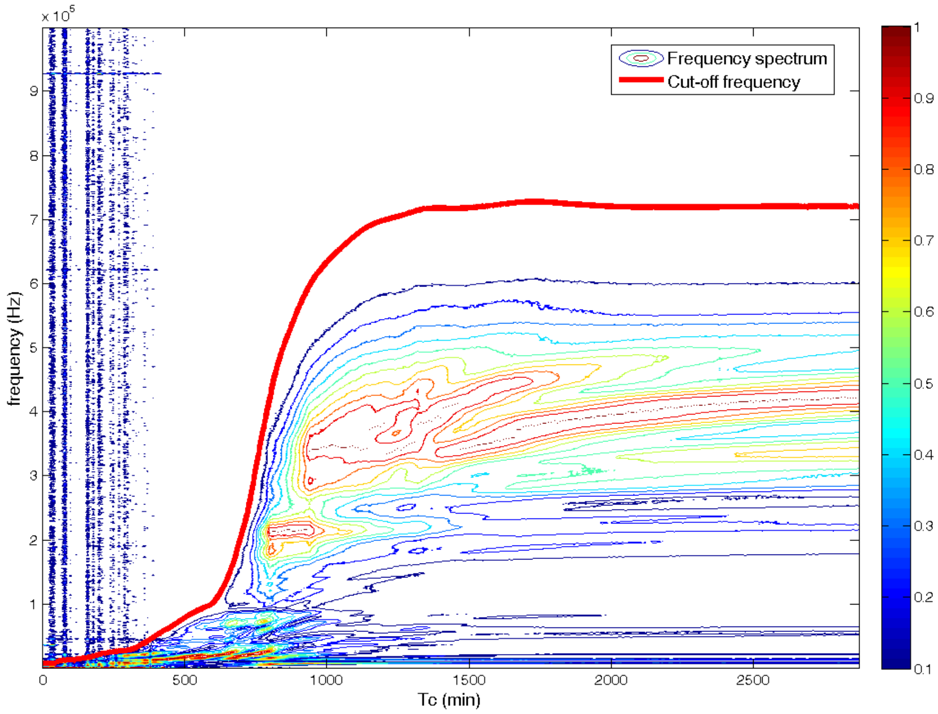


Figure D.10 Frequency spectrum and final cut-off frequency for SCM C1-S2-070-F3-075

D.3 Bessel filter

In electronics and signal processing, a Bessel filter is a type of linear filter with a maximally flat group delay (maximally linear phase response). Analog Bessel filters are characterized by an almost constant group delay across the entire passband, thus preserving the wave shape of filtered signals in the passband. In this case it is very important to preserve the US wave shape, and avoid big phase shapes which could produce a delay in the arrival time of the filtered signal.

A Bessel low-pass filter is characterized by its transfer function:

$$H(s) = \frac{\theta_n(0)}{\theta_n(s/\omega_0)}$$

where θn(s) is a reverse Bessel polynomial from which the filter gets its name and ω_0 is a frequency chosen to give the desired cut-off frequency. The filter has a low-frequency group delay of 1 / ω_0.

The reverse Bessel polynomials are given by:

$$\theta_n(s) = \sum_{k=0}^{n} a_k s^k$$

where [13]

$$a_k = \frac{(2n-k)!}{2^{n-k}k!\,(n-k)!} \quad k = 0,1,\dots,n$$

The Bode diagram in *Figure D.11* shows different continuous Bessel filters for a cut-off frequency of 100 kHz. In spite of the fact that it is very important to keep the received wave shape, and avoid delays, the best option is a first order Bessel filter. In its cut-off frequency, it has an attenuation of -3dB (Gain=0.71) and a delay of 45°.

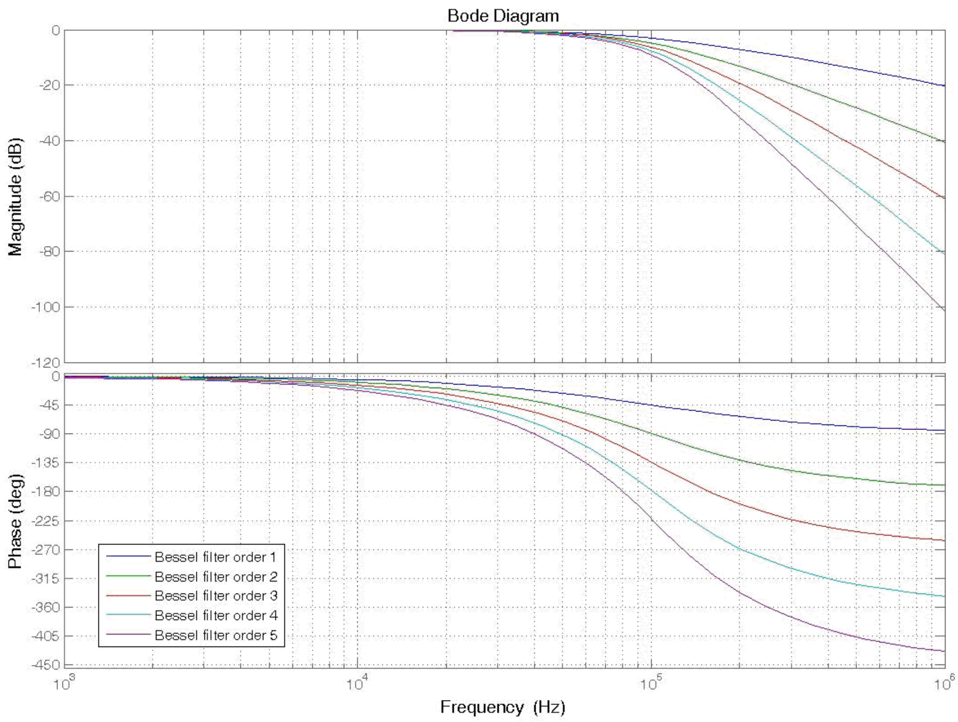


Figure D.11 Bessel filters with different order

It is necessary to work with a discrete filter since the pre-filtered signal is a discrete signal with a sampling frequency of 10MHz. The filter is discretized using Tustin discretization. The Tustin method typically performs better than other methods in the frequency domain because they introduce less gain and phase distortion near the Nyquist frequency. The Tustin method uses a bilinear transformation to compute the discretized model. This method rounds fractional delays to the nearest integer multiple of the sampling period [14] [15]. Because the Nyquist frequency of the system (5 MHz) is much bigger than the US signal frequencies (<700 kHz), the Tustin discretized Bessel filter is an appropriate choice, and an accurate approximation of the continuous filter.

D.4 Grouped signal calculation

If received signals in young concrete are filtered without another treatment, the obtained filtered signals are still noisy (*Figure D.14*), and the AIC picker onset time detection is still troublesome. Therefore it is necessary to apply another treatment to improve the situation and to attenuate the noise in the received signal. Following the principle of Freshcon of calculating the mean of 3 signals to compose the received signal, the mean of 3, 7 or 11 signals is calculated to obtain a final grouped signal (*Figure D.12* and *Figure D.13*). This is an effective way of reduction of noise amplitude without producing delays. Velocity curves are flat and change very gradually in this first period with low Tc. Therefore, the fact of calculating the mean of signals sent in different time moments reduces its effect on the solution. After calculating the mean of several signals the grouped signal is filtered in the same way that single signals are filtered.

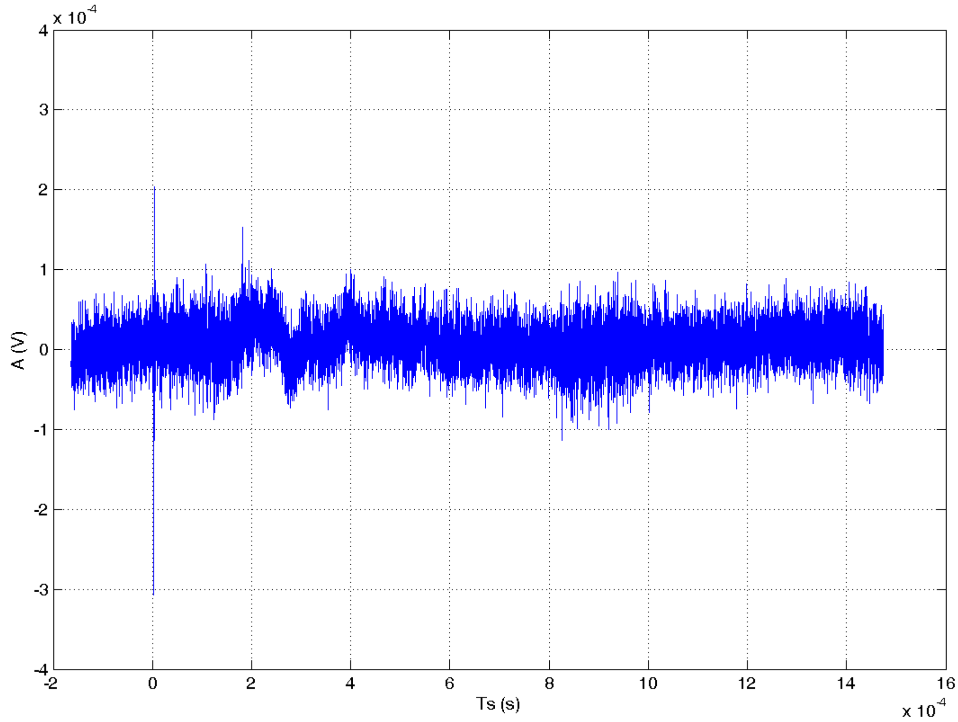


Figure D.12 Original signal with Tc = 200 min for SCM C1-S2-070-F3-075

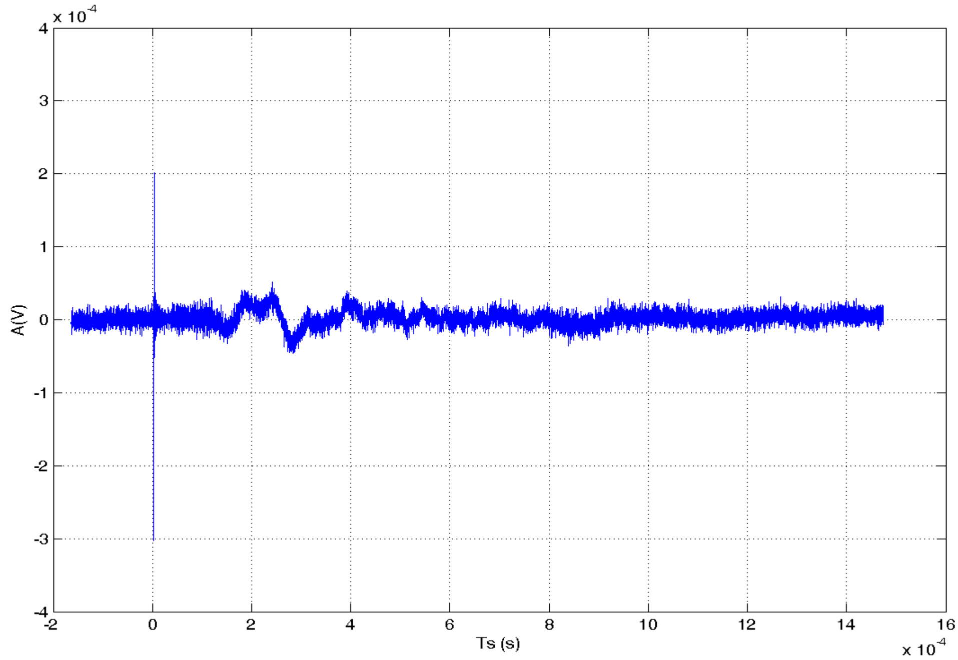


Figure D.13 Composed signal calculated with the average of 7 signals with Tc = 200 min for SCM C1-S2-070-F3-075

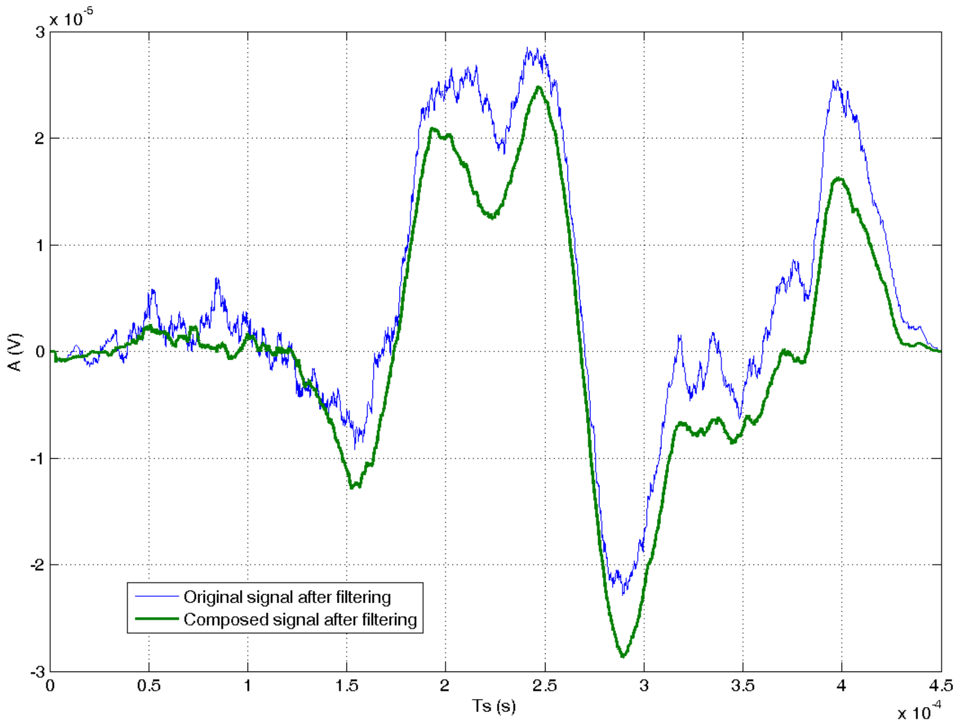


Figure D.14 Original and composed signal after filtering with Tc = 200 min for SCM C1-S2-070-F3-075

Depending on the age of the cementitous mixture, the signals are treated in different way before being filtered. But this determination it is not easy: some experience with the mixtures with similar composition is needed is order to determine an appropriate treatment of the signals. It is necessary to have a gross estimation (± 100 min) of the inflection point of the curve. To determine the 4 different treatments which are applied to the signals, it is necessary to establish 3 frequency levels: L1, L2 and L3 which corresponds to the average of L1 and L2. From signals in older to younger mixture, they are treated in these ways (*Figure D.15*):

- Original signals keep their original state: Signal with a filter's cut-off frequency higher than frequency level L1.
- A grouped signal is created calculating the mean of 3 signals: Signal with a filter's cut-off frequency between L3 and L1.
- A grouped signal is created calculating the mean of 7 signals: Signal with a filter's cut-off frequency between L2 and L3.
- A grouped signal is created calculating the mean of 11 signals: Signal with a filter's cut-off frequency lower than frequency level L1.

To perform these four different treatments of the signals it is necessary to establish two frequency levels L1 and L2:

- L1: Frequency level 1 (Hz): For the big holder, the cut-off frequency of 2/3 of the estimated start of percolation time can be a reference. For the small one 1/3 of the estimated start of percolation time is enough to obtain clear signals, because the noise/signal rate is lower. Obviously the start of percolation is not known before analyzing the test results. It is necessary to have some experience with similar mixtures. If there isn't any previous experience, the beginning of the steeper zone in the cut-off frequency profile could be also a reference. Anyway, the consequences of a too high frequency level 1 are a slower process and an unnecessary treatment of the signals, but the velocity results don't change in a significant way. On the other hand, a too low level produces noisy signals which make difficult the AIC picker work and it leads to lower and more irregular velocities values. Therefore, if the user has no other reference, it is better to estimate a high start of percolation time.

- L2: Frequency level 2 (Hz): Usually filter's cut-off frequency is flat in the first minutes. Frequency level 2 should be slightly higher than this cut-off frequency. If it is not the case, frequency level 2 should be the cut-off frequency at 1/3 of the time of cut-off frequency equal to frequency level 1.

$$L_2 = f_{cut-off}\left(\frac{1}{3}\,t\left(f_{cut-off} = L_1\right)\right)$$

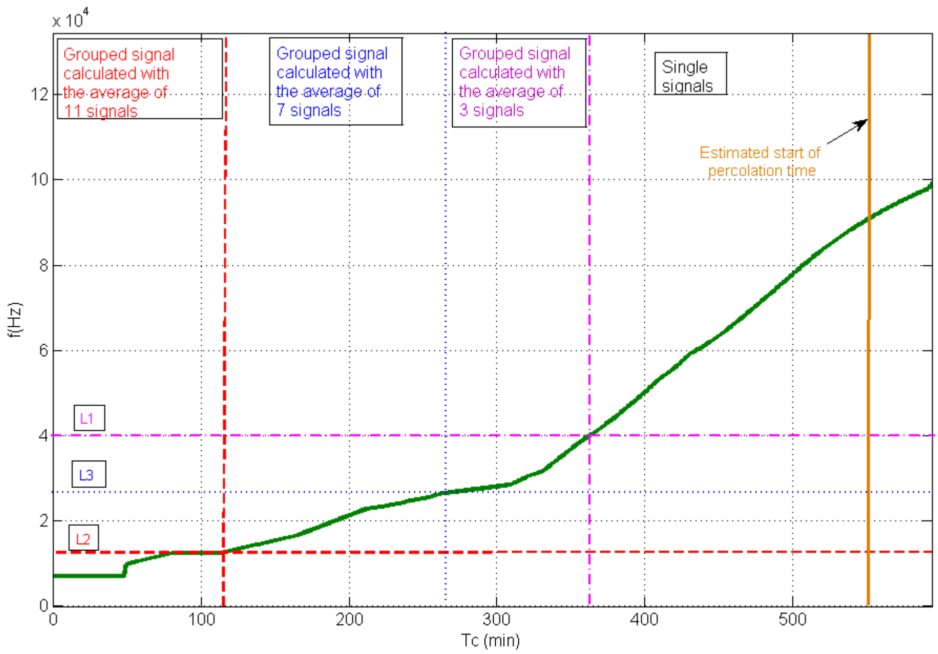


Figure D.15 Frequency levels to determine the different treatments of the signals using the cut-off frequency curve

D.5 Cross correlation

Filtering the received signals produces clearer signals and reduces the AIC picker delays. The fact of using a filter introduces new delays, due to the phase shift of causal filters. The advantage of this delay, comparing with the delay in the AIC picking algorithm, is that it is possible to measure the shift, and correct it, by means of the cross correlation. The cross-correlation is applied to the pre-filtered signal and its corresponding filtered signal and the delay between them is calculated, by determination the maximum of the cross correlation function.

In signal processing, cross-correlation is a measure of similarity of two waveforms as a function of a time-lag applied to one of them. This is also known as a sliding dot product or inner-product. It is commonly used to search a long duration signal for a shorter, known feature. It also has applications in pattern recognition, single particle analysis, electron tomographic averaging, cryptanalysis, and neurophysiology.

For discrete functions, the cross-correlation is defined as:

$$(f \circ g)[n] = \sum_{m=-\infty}^{\infty} f^*[m]\, g[n+m]$$

The cross-correlation is similar in nature to the convolution of two functions. Whereas convolution involves reversing a signal, then shifting it and multiplying by another signal, correlation only involves shifting it and multiplying (no reversing).

For example, consider two real valued functions f and g that differ only by an unknown shift along the x-axis. One can use the cross-correlation to find how much g must be shifted along the x-axis to make it identical to f. The formula essentially slides the g function along the x-axis, calculating the integral of their product at each position. When the functions match, the value of (f*g) is maximized. The reason for this is that when peaks (positive areas) are aligned, they make a large contribution to the integral. Similarly, when troughs (negative areas) align, they also make a positive contribution to the integral because the product of two negative numbers is positive [16].

The calculation of the filter delay by means of the cross correlation can be illustrated with a real example. *Figure D.16* shows an original signal and a filtered signal. The cross correlation procedure shifting the signals is applied to these two signals, and the cross correlation function is obtained (*Figure D.17*). Since it is a discrete system, this function has discrete value for each time sample. The maximum of the function determines the delay between both signals, in this case, 18 samples or 1.8 µs.

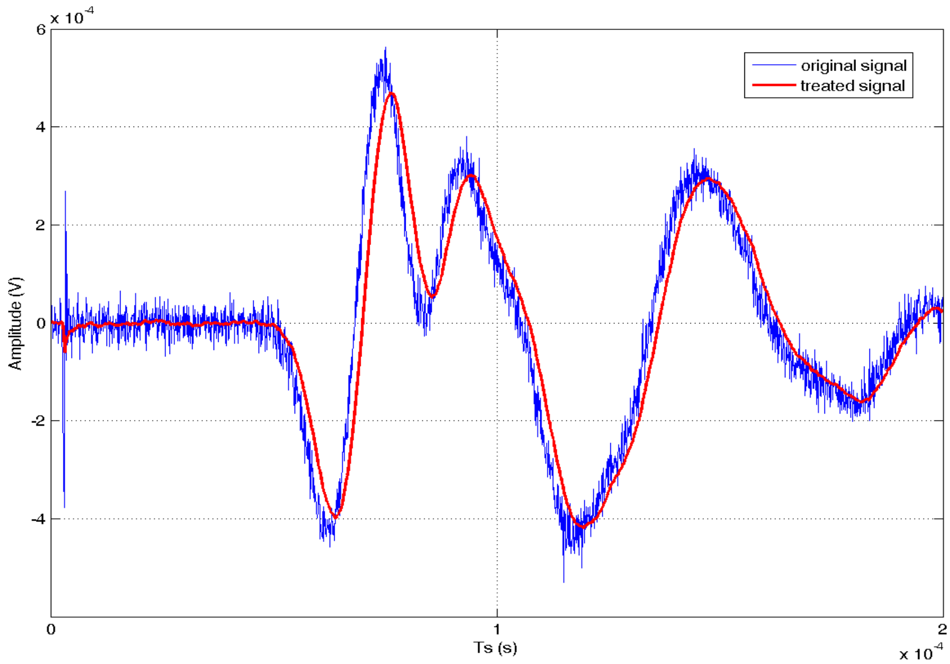


Figure D.16 Original and treated signal with a delay of 1.8 µs at Tc= 500 min for SCM C1-S2-070-F3-075

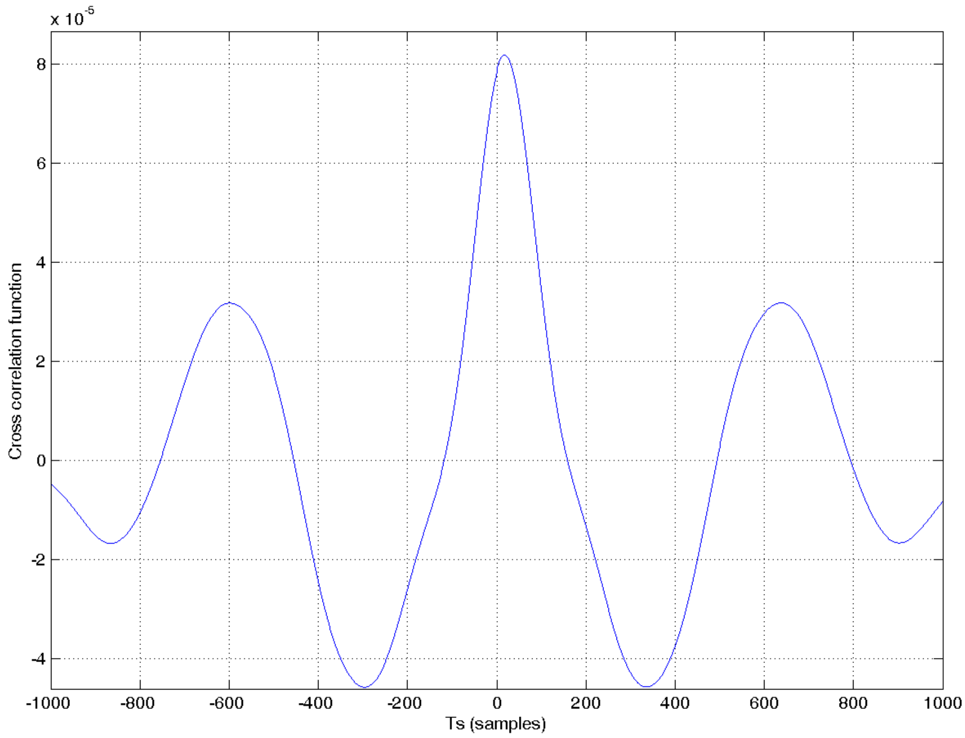


Figure D.17 Cross correlation function whose maximum is at sample 18

D.6 Post-filtering treatment

The filtered signal is still treated after being filtered. The objectives of this treatment are to avoid three of the problems described in the introduction:

1. To make the AIC picker calculation faster analyzing only the interesting part of the received signals
2. Elimination of the problems caused by the trigger in young cementitous mixtures
3. To avoid problems with signals which have high amplitude at the end, caused for example by a drift in the signal.

This treatment consists in taking the desired part of the signal of sz samples, and multiplying the first lw samples by a linear growing factor and the last hw samples by a linear decreasing factor. It means that the filtered signal is multiplied by a trapezoidal window as *Figure D.18* shows.

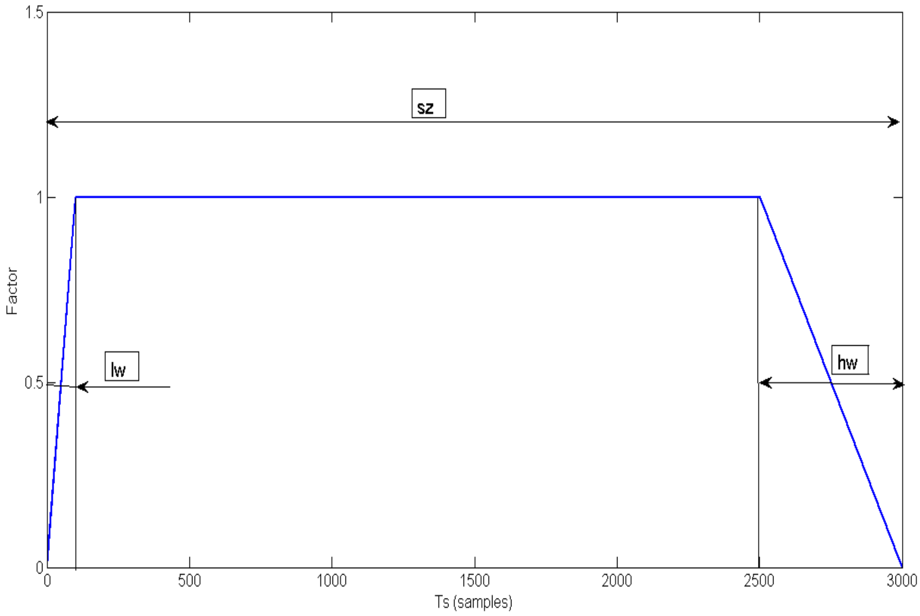


Figure D.18 Trapezoidal window applied to the filtered signals

First of all, only the part of the received signal containing the time counter, trigger, onset time and US received signal is taken. Since calibration time values obtained in the laboratory are always positive, a number of sz samples starting from Ts=0.1µs sample is necessary to be set to take the correct part of the signal. For raw signals and grouped signals with an average of 3 signals (from Tc=290 min until 2880 min), the size (sz) of the signal containing the desired elements is 3000 samples (*Figure D.19* and *Figure D.20*). For grouped signals with an average of 7 and 11 signals (Tc lower than 290 min) the size of the signal is 4500 samples (*Figure D.21*).

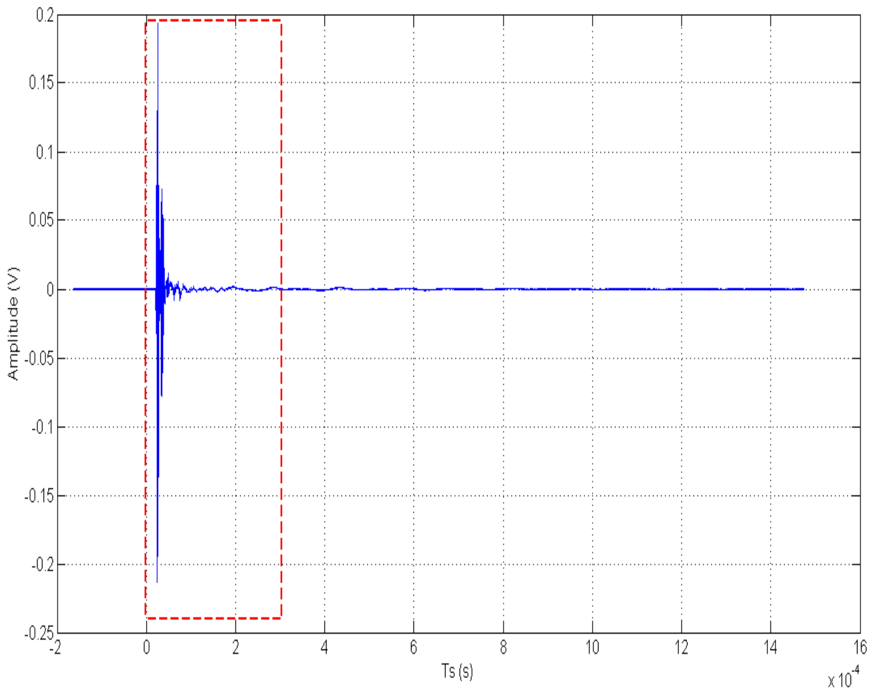


Figure D.19 Selected part of the signal at Tc=2879 min for SCM C1-S2-070-F3-075

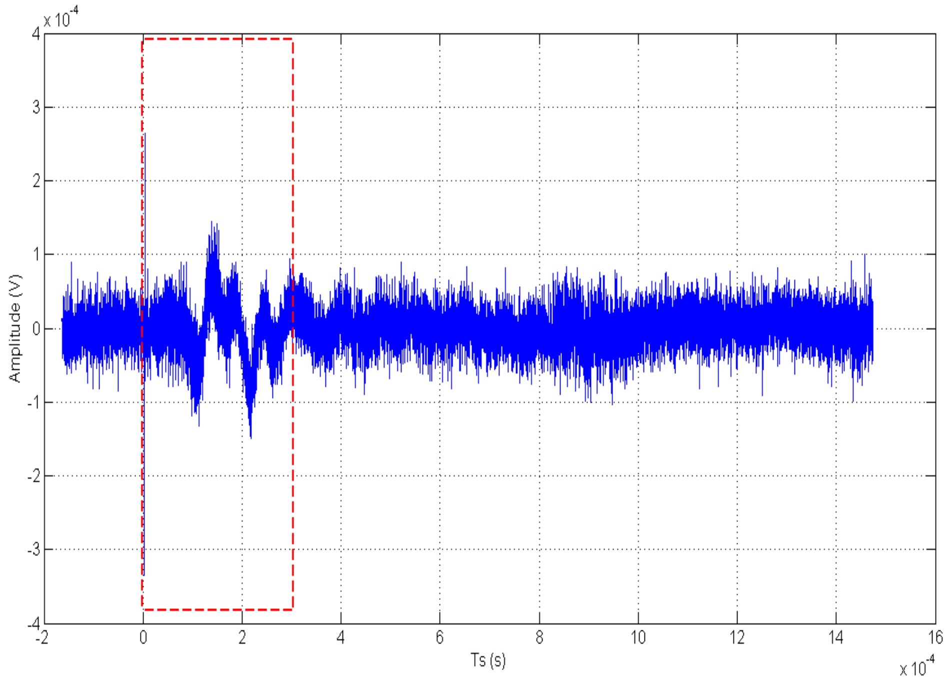


Figure D.20 part of the signal at Tc=300 min for SCM C1-S2-070-F3-075

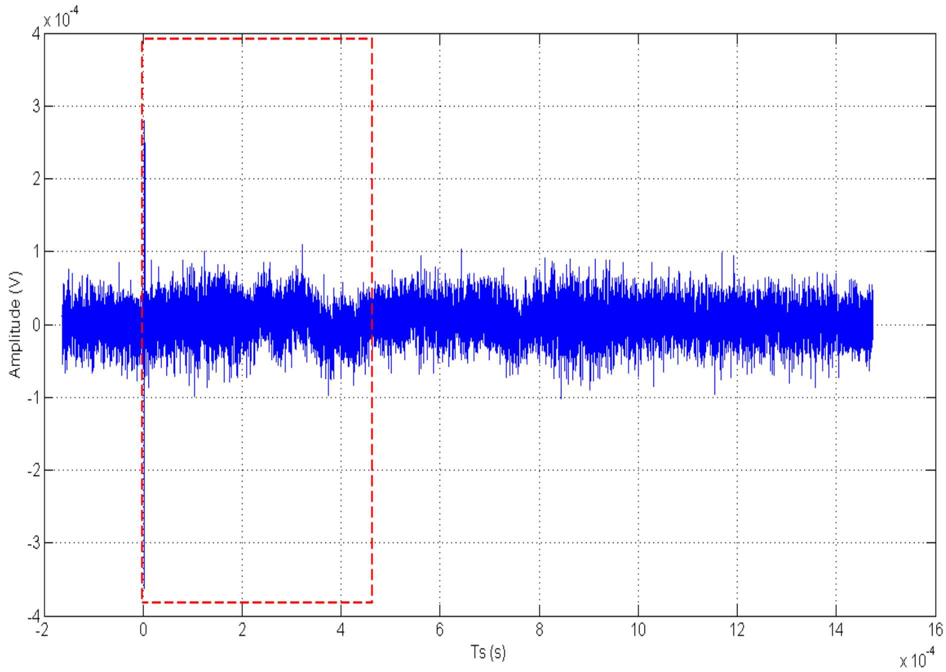


Figure D.21 Selected part of the signal at Tc=100 min for SCM C1-S2-070-F3-075

Secondly, the trigger is attenuated by multiplying the first lw of the sz samples of the filtered signal, which contain the trigger but not the US received signal. Let's consider the case of the big holder with a distance of 55 mm between transducers and a calibration time of 8.6 µs (86 samples) and the different values:

- For filtered single signals and grouped signals calculated with the average of 3 signals, the maximum velocity of the signal maximally could be 5000 m/s after 2 days. This corresponds to a real onset time of 110 samples (11 µs). If the calibrated onset time and the calibration time are added, it leads to an onset time of 196 samples starting from registered time counter sample. Therefore a value of lw=100 samples is set, 50% lower than possible. In this case, the worst case scenario would be one of the youngest grouped signals calculated with the average of 3 signals, where the amplitude of the US received signal is low and lw is very low compared with the calibrated onset time. In *Figure D.22* it can be seen that the trigger is around 6 times smaller than the first semiperiod of the signal, so it doesn’t interfere with the preliminary calibrated onset time calculation with a threshold level of 0.2.

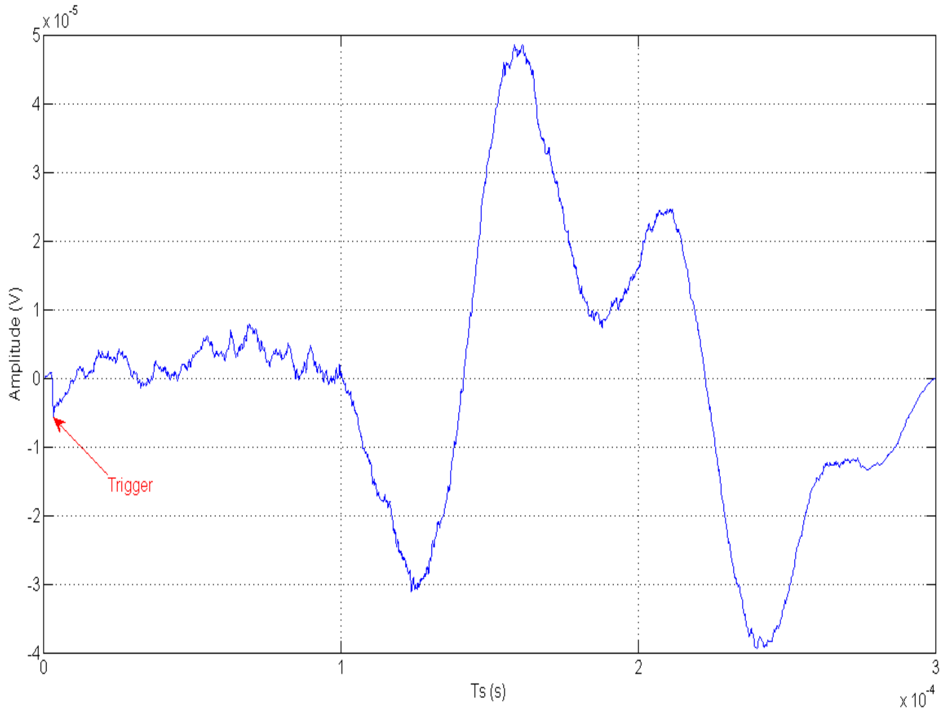


Figure D.22 Treated signal (grouped with 3 signals) at Tc = 265 min for SCM C1-S2-070-F3-075

- For grouped signals calculated with the average of 7 signals, the maximum velocity of the signal could be 1000 m/s (it is supposed that at start of percolation time speed is around 1500 m/s). This corresponds to a real onset time of 550 samples (55 µs). If the calibrated onset time and the calibration time are added, it leads to an onset time of 636 samples starting from registered time counter sample. Therefore a value of lw=300 samples is set, 50% lower than the onset time. In this case, the worst case scenario would be one of the youngest grouped signals calculated with the average of 7 signals, where the amplitude of the US received signal is low and lw is very low compared with the calibrated onset time. In *Figure D.23* it can be seen that the trigger cannot be distinguish from the remaining noise, so it doesn’t interfere with the preliminary onset time calculation with a threshold level of 0.2.

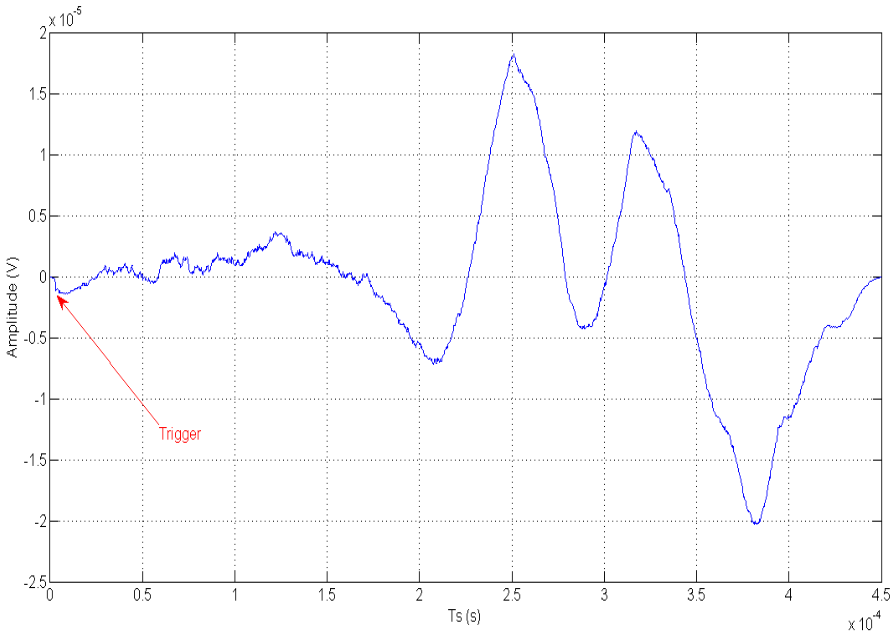


Figure D.23 Treated signal (grouped with 7 signals) at Tc = 120 min for SCM C1-S2-070-F3-075

- For grouped signals calculated with the average of 11 signals, the maximum velocity of the signal could be 500 m/s (initial speeds in mortars are under 400 m/s). This corresponds to a real onset time of 1100 samples (110 µs). If the calibrated onset time and the calibration time are added, it leads to an onset time of 1186 samples starting from registered time counter sample. Therefore a value of lw=500 samples is set, 60% lower than the in-between time. In this case, the worst case scenario would be one of the youngest grouped signal calculated with the average of 11 signals, where the amplitude of the US received signal is low and lw is very low compared with the onset time. In *Figure D.24* it can be seen that the trigger is much smaller than the remaining noise, so it doesn't interfere with the preliminary onset time calculation with a threshold level of 0.2.

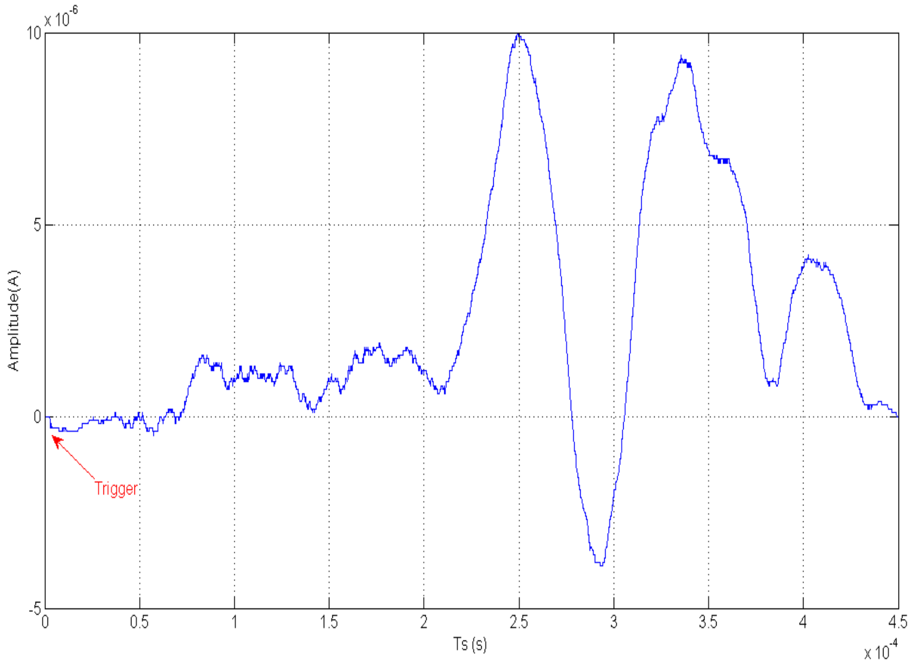


Figure D.24 Treated signal (grouped with 11 signals) at Tc = 10 min for SCM C1-S2-070-F3-075

Finally, the last hw samples of the treated signal are attenuated in order to avoid a maximum in the envelope of the Hilbert transform at the end of the signal in case of a external low frequency wave. hw is set to 500 samples for all the filtered signals. As it can be seen the precedent 3 figures, it is an appropriate value which doesn't attenuate the first semiperiods of the US received signal.

D.7 Freshcon offline

Using Freshcon offline software a velocity curve file is obtained calculating the onset time of the treated signal using AIC picker functions with the following parameters:

- The detection of the onset time is performed using the AIC picker algorithm in *automatic* mode and with the *Invert data sorting* option selected.
- The *threshold* of the AIC picker applied in the normed envelope and used to prearrange the preliminary onset time of the signal is set to 0.2. Sometimes, if the trigger amplitude is too big in signals in young concrete, this value should increase until 0.3 or more.
- The bounds of the window in which the AIC function is calculated have to vary during the calculation process of the velocity curve, because the onset time increases in this calculation (*Invert data sorting* option has been previously selected). The *window upper bound* can be set to 150 samples. At the beginning of the calculation, the *window lower bound* should be set to 100 samples for the small container and 200 samples for the big one. Then it should be increased manually having values approximately of the sample's number of the onset time.
- In the window where the AIC function is calculated, some samples don't have to be considered to determine the minimum of this function, because it is known that the signal cannot arrive at this time. The *AIC lower bound* is set to 50 samples for the small holder and 100 samples for the big one. The *AIC upper bound* is set to 150 samples, the same value of the *window upper bound*.

D.8 Velocity correction

Velocities are corrected in three different ways:

- The delay is subtracted to the Freshcon calculated arrival time of the signal
- The velocity is calculated with the real distance between transducers and not with the default Freshcon setting distance.
- A manual cleaning is performed to eliminate peaks in the curve

Figure D.25 shows the final obtained velocity curve. The curve is irregular and noisy and it has also little slumps. To obtain a smooth gradient to determine the inflection point of the curve it is necessary to fit a smooth curve in the obtained data, for example a combined logistic function.

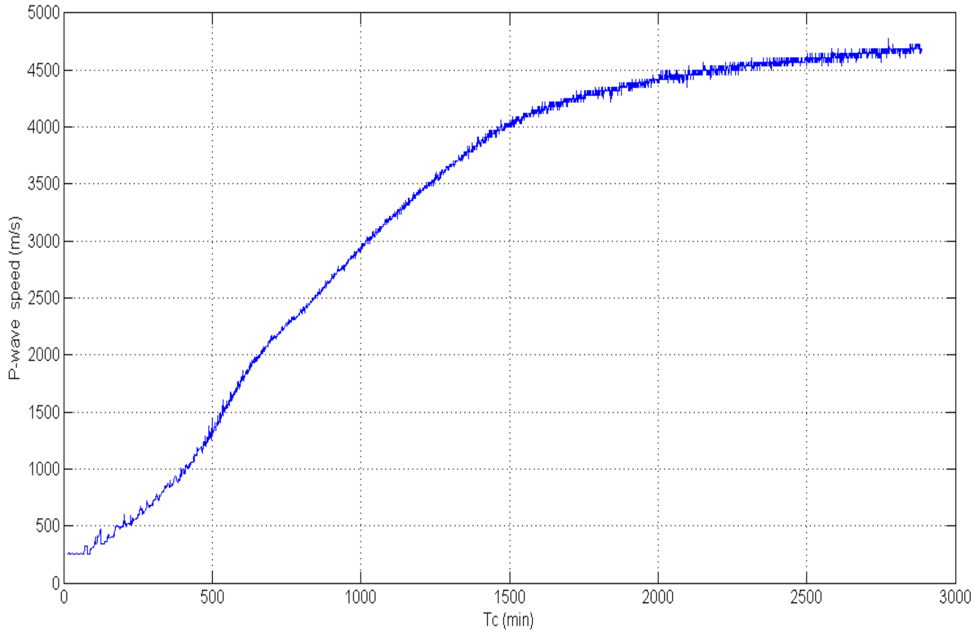


Figure D.25 P-wave velocity curve for SCM C1-S2-070-F3-075

D.9 Checking of the obtained results

After obtaining a final curve velocity (C1-S2-040-F3-075), it is necessary to check if the obtained curve fits with the manual picking speed curve taken at the beginning as reference. As it can be noticed in *Figure D.26*, the AIC picker velocity obtained from the original data is always lower than the velocity obtained from treated data. Moreover, the AIC picker velocity obtained from treated data fits perfectly with the possible manual picking velocity. In the few cases, there is bad correspondence; but the difference is only a delay of one sample in the onset detection. These small problems happen during the hardening of the mixture in the second day of the US test, far away from the setting and start of percolation time around 500-700 minutes for this mixture, and the obtained speed is always closer to the real one than AIC picker velocity using original data.

In addition, while working directly with the original data it is impossible to determine a velocity in signals in mortar younger than 400 minutes with AIC picker and 250 minutes with manual picking, it is possible to obtain velocity speeds after few minutes working with AIC picker algorithm with the treated data, and consequently obtain a S-shape velocity curve, which helps to determine the maximum gradient of the curve more easily.

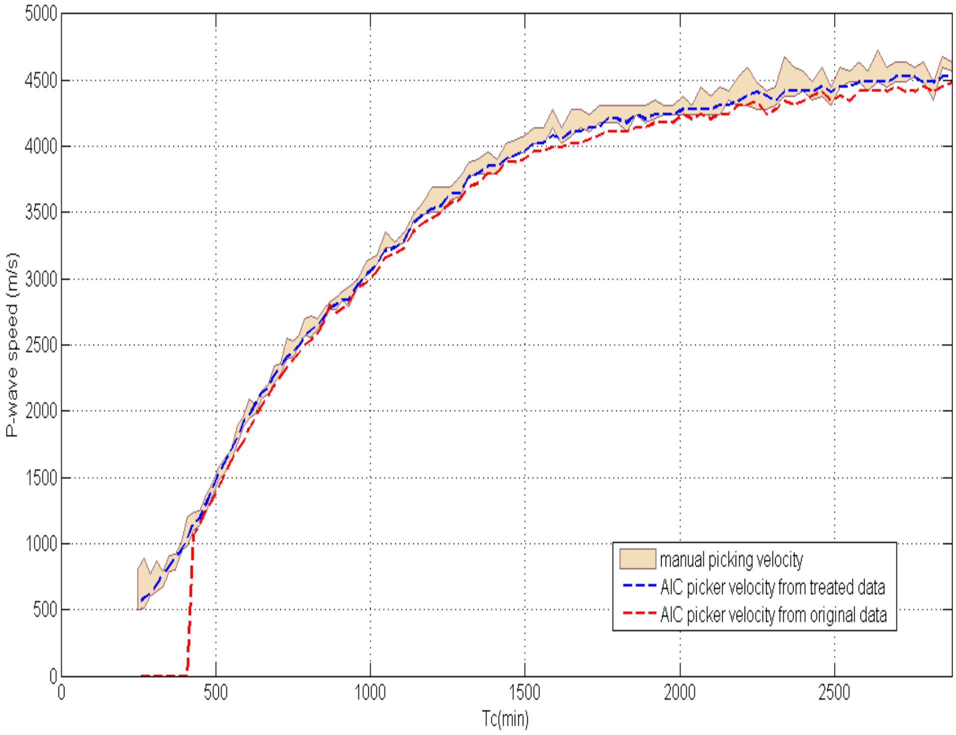


Figure D.26 P-wave velocity curve before and after the treatment of the data for SCM C1-S2-040-F3-075

Anexo E

E. Ensayos realizados

E.1 Ensayos sobre mortero auto-compactante en estado fresco

E.1.1 Tipos de ensayo realizados

Las distintas mezclas de SCM han sido sometidas a ensayos en el laboratorio en estado fresco, pocos minutos tras la adición de agua a la mezcla cuando el proceso de hidratación del cemento todavía está en la fase durmiente. Debido a la disponibilidad de dispositivos para la medición de propiedades frescas del laboratorio, se ha estudiado la fluidez y consistencia del SCM mediante ensayos mediante flow table, el contenido en aire mediante el método manométrico y la densidad, que a continuación son descritos.

Antes de ensayar el mortero fresco es necesario formar la mezcla siguiendo un procedimiento establecido de manera repetible y reproducible. El siguiente procedimiento de mezcla es seguido:

- Primero, se deposita los siguientes materiales en el recipiente metálico por capas: arena normalizada según la norma DIN EN 196-1 (aproximadamente la mitad de 1350g totales), ceniza volante, cemento portland CEM I 52,5N y arena normalizada (la mitad restante).
- Segundo, se mezcla en seco con la mezcla con la mezcladora automática Controls 65-L0006/A (*Figura E. 1*) a 140 r.p.m. durante 1 min.
- Se añade el agua (202,5 g a una temperatura de 20ºC) durante 30 s mientras se sigue mezclando a 140 r.p.m.
- Posteriormente, se mezcla a 140 r.p.m. durante 30 s.
- Se deja reposar la mezcla durante 30 s y se añade el SP.
- A continuación, se mezcla a 285 r.p.m. durante 30 s.
- Se deja reposar la mezcla durante 90 s y se limpia el borde del recipiente.
- Finalmente, se mezcla a 285 r.p.m. durante 1 min.

Figura E. 1 Mezcladora automática Controls 65-L0006/A

E.1.2 Ensayos de consistencia

La consistencia del hormigón fresco se puede medir gracias a la flow table. La consistencia es una medida de la fluidez del y/o humedad y da una medida de la deformabilidad del mortero fresco sometido a una cierta tensión. Sin embargo, la consistencia no es una medida directamente asociada a la facilidad de trabajar manualmente el mortero.

El valor del slump flow test es el valor del diámetro medio de un muestra de hormigón fresco que ha sido colocado en una flow table estándar dentro de un molde cónico estándar, y que ha sido dejado fluir libremente al levantar el molde. El valor del flow test es el valor del diámetro medio de la muestra tras aplicar 15 impactos verticales en 15 s, tras haber medido el valor de slump flow test, elevando hasta una cierta altura y dejando caer por su propio peso la flow table (*Figura E.2*). Los valores mínimos del slump flow test y flow test son de 100 mm que corresponden al diámetro inferior del molde cónico, los valores máximos son de 300 mm correspondientes al diámetro de la flow table [19].

En la actualidad existe un estándar para mortero para la realización del flow test (EN 1015-3) donde esta detallada toda la información necesaria para su ejecución, pero no todavía para la realización del slump flow test. Sin embargo, el slump flow test está considerado una mejor medida de la consistencia del SCM, ya que el SCM no necesita de ningún aporte energético como vibrado para su completa compactación.

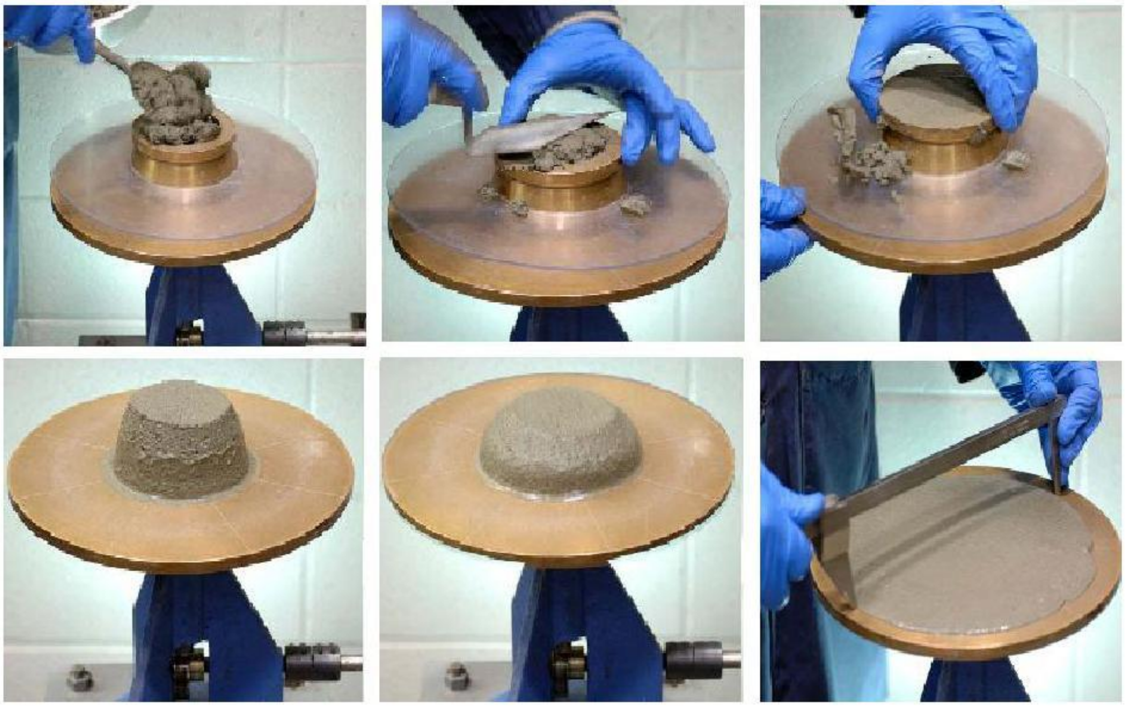


Figura E.2 Procedimiento de ensayo de la consistencia de mortero fresco

E.1.3 Ensayos de contenido en aire

El estándar europeo EN 1015-7 establece el método manométrico como el apropiado para morteros frescos con un contenido menor al 20% en volumen, como es el caso de los SCM. Un volumen de mortero es emplazado en un recipiente metálico de aproximadamente 1l

(*Figura E.3*). Se introduce agua sobre la superficie superior de la muestra de mortero, y por medio de la aplicación de una presión mediante aire, el agua es forzada a introducirse en la mezcla de mortero rellenando los poros del mismo. Por eso, el nivel de agua baja en el recipiente y refleja el volumen de aire desalojado del mortero, es decir, el contenido de aire del mortero previo al ensayo [20].

Figura E.3 Dispositivo para la medición por el método manométrico del contenido en aire de mortero

E.1.4 Ensayos de densidad

El estándar europeo EN 1015-6 especifica el método para determinar la densidad de muestras de mortero fresco. La densidad de una muestra de mortero está determinada por el cociente de la masa y el volumen que ocupa cuando es introducida o introducida y compactada de la manera descrita en el estándar en un recipiente de medida con una cierta capacidad [21].

E.2 Resultados de los ensayos realizados

E.2.1 Influencia de la variación de la cantidad de Glenium 51

% SP (Glenium 51)	0.4	0.5	0.55	0.6	0.65	0.7	0.8	0.9	1.0	1.1
Slump flow 1a (mm)	100	100	100	161	260	278	295	290	300	300
Slump flow 1b (mm)	100	100	100	165	266	280	300	295	300	300
Slump flow 2a (mm)	100	100	100	218	255	280	300	300	295	300
Slump flow 2b (mm)	100	100	100	220	264	283	300	300	300	300
Slump flow 3a (mm)	100	100	100	196	256	280	277	281	284	300
Slump flow 3b (mm)	100	100	100	190	258	279	279	282	286	300
Media Slump flow (mm)	100	100	100	192	260	280	292	291	294	300
Flow 1a (mm)	131	145	157	205	277	300	300	300	300	300
Flow 1b (mm)	135	147	157	207	280	300	300	300	300	300
Flow 2a (mm)	131	146	148	248	272	300	300	300	300	300
Flow 2b (mm)	128	149	150	252	278	300	300	300	300	300
Flow 3a (mm)	126	134	151	223	282	300	300	300	300	300
Flow 3b (mm)	125	134	152	222	284	300	300	300	300	300
Media Flow (mm)	129	143	153	226	279	300	300	300	300	300
Contenido aire (% vol.)	6	5.4	5.8	5.3	4.9	5	3.5	2	1.1	1.7
Densidad (kg/m^3)	2200	2190	2220	2230	2220	2260	2250	2240	2290	2280
Tiempo comienzo percolación (min)	502	519	-(5)	543(6)	-	X(7)	564	631	630	675

Tabla E.1 Resultados del estudio paramétrico de la cantidad de SP Glenium 51 en SCM con cenizas volantes

(5) Ensayo no realizado

(6) Resultado obtenido del estudio paramétrico de la cantidad de cenizas volantes (Tabla E.2)

(7) Ensayo cuyo resultado es incorrecto

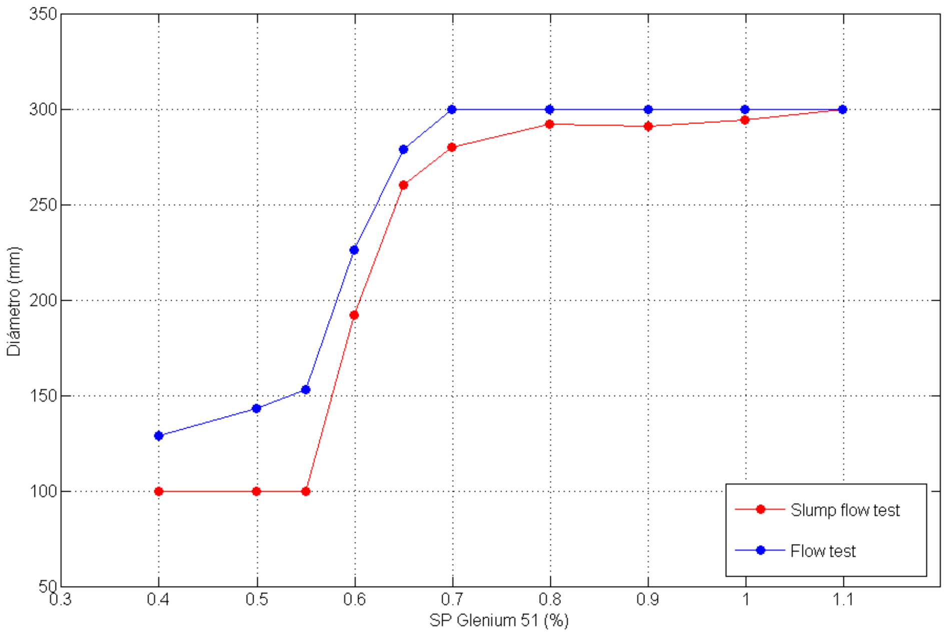


Figura E.4 Ensayos de fluidez del estudio paramétrico de la cantidad de SP Glenium 51 en SCM con cenizas volantes

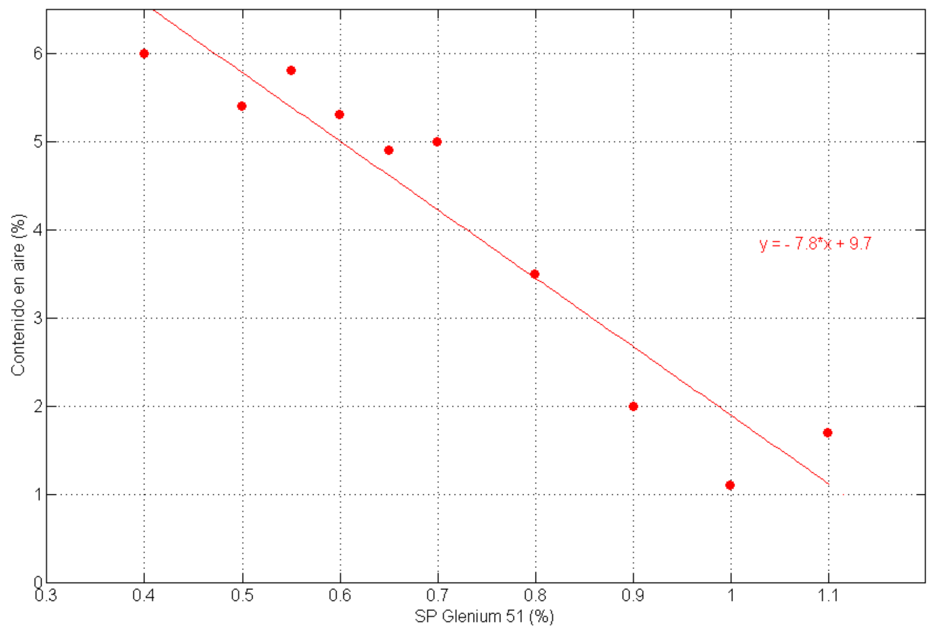


Figura E.5 Ensayos de contenido de aire del estudio paramétrico de la cantidad de SP Glenium 51 en SCM con cenizas volantes

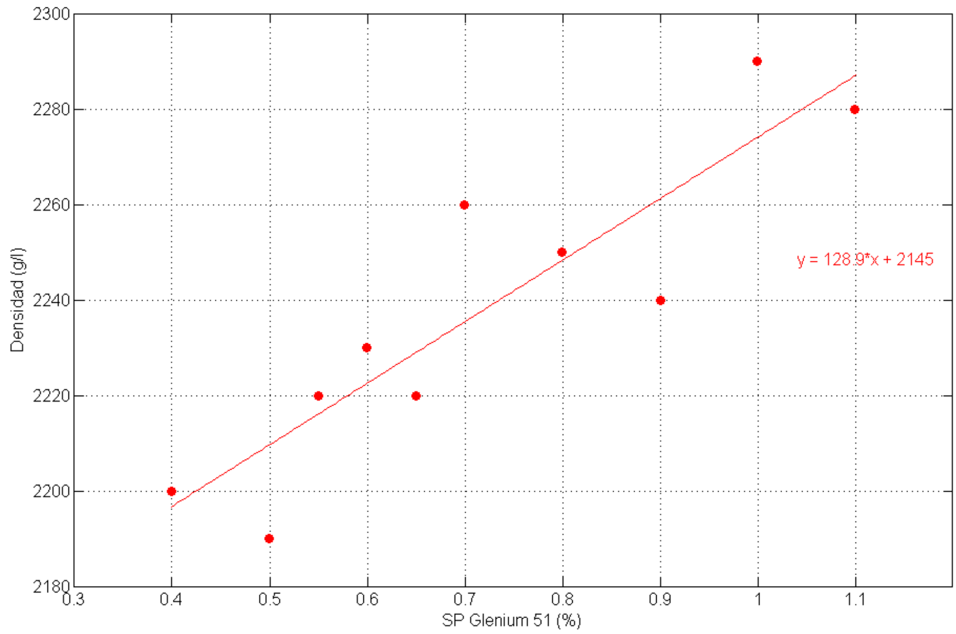


Figura E.6 Ensayos de densidad del estudio paramétrico de la cantidad de SP Glenium 51 en SCM con cenizas volantes

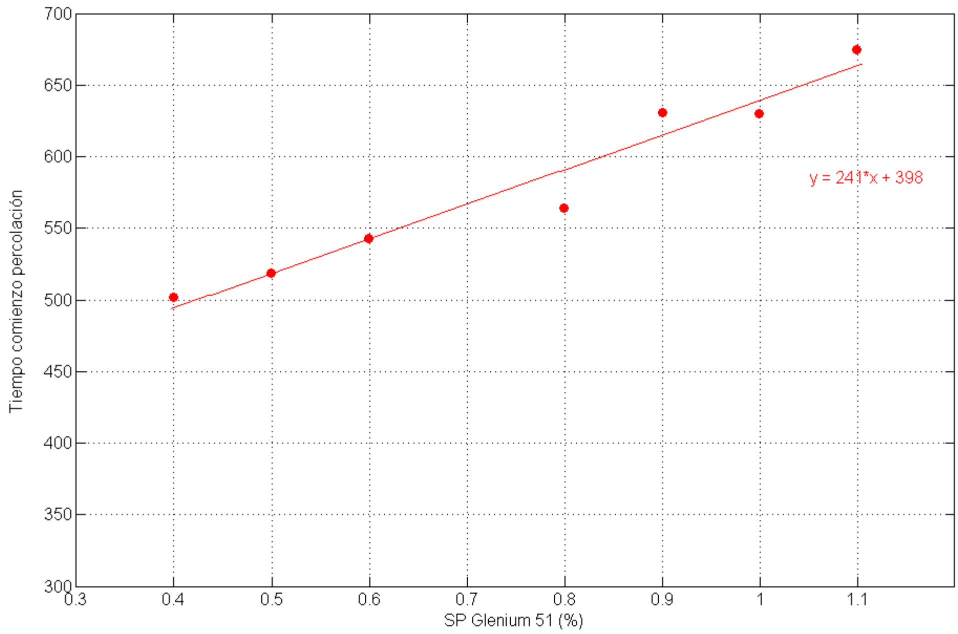


Figura E. 7 Resultados del tiempo de comienzo de percolación con dispositivo de monitorización US del estudio paramétrico de la cantidad de SP Glenium 51 en SCM con cenizas volantes

E.2.2 Influencia de la variación de cenizas volantes

C/P (con Glenium 51)	0.662	0.682	0.703	0.726	0.75	0.776	0.804	0.833	0.865
Slump flow 1a (mm)	100	100	168	187	249	267	276	282	278
Slump flow 1b (mm)	100	100	179	192	252	271	270	281	285
Slump flow 2a (mm)	100	100	136	192	229	262	274	274	274
Slump flow 2b (mm)	100	100	120	201	242	257	270	284	276
Slump flow 3a (mm)	-	100	100	180	185	257	270	-	-
Slump flow 3b (mm)	-	100	100	174	183	259	262	-	-
Media Slump flow (mm)	100	100	134	188	223	262	270	280	278
Flow 1a (mm)	153	190	243	238	281	290	288	290	300
Flow 1b (mm)	150	191	244	233	276	296	292	300	300
Flow 2a (mm)	143	161	192	240	270	284	286	290	290
Flow 2b (mm)	140	163	176	250	262	289	295	298	300
Flow 3a (mm)	-	143	164	209	221	281	288	-	-
Flow 3b (mm)	-	144	176	216	222	285	275	-	-
Media Flow (mm)	147	165	199	231	255	288	287	295	298
Contenido aire (% vol.)	6.2	5.9	5.1	5.1	5.2	4.6	2.5	1.8	1.7
Densidad (kg/m^3)	2210	2210	2230	2240	2230	2220	2240	2290	2280
Tiempo comienzo percolación (min)	-	563	X	538	543	X	472	340	-

Tabla E.2 Resultados del estudio paramétrico de la cantidad de cenizas volantes en SCM con SP Glenium 51

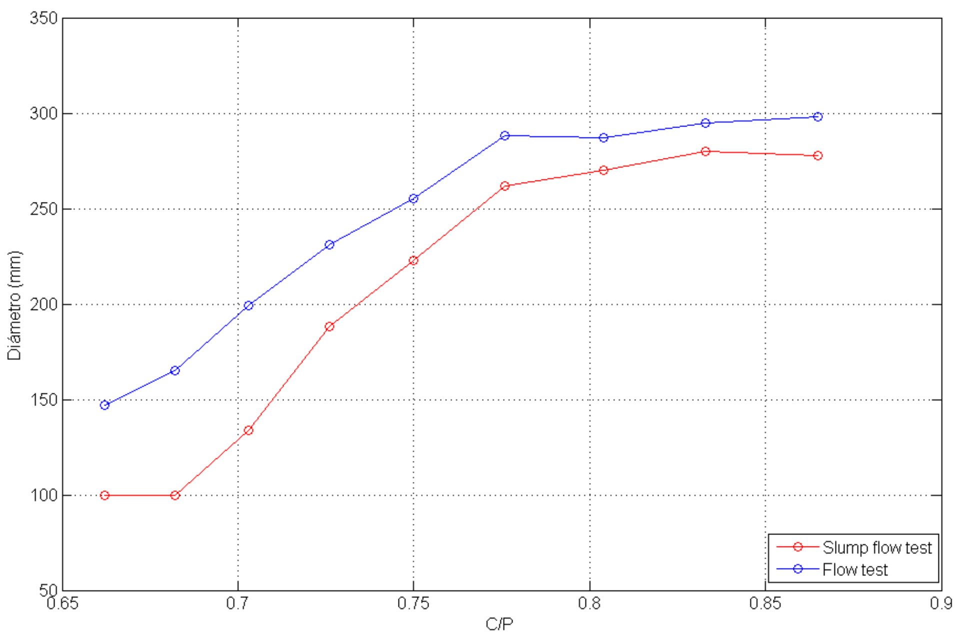


Figura E.8 Ensayos de fluidez del estudio paramétrico de cenizas volantes en SCM con SP Glenium 51

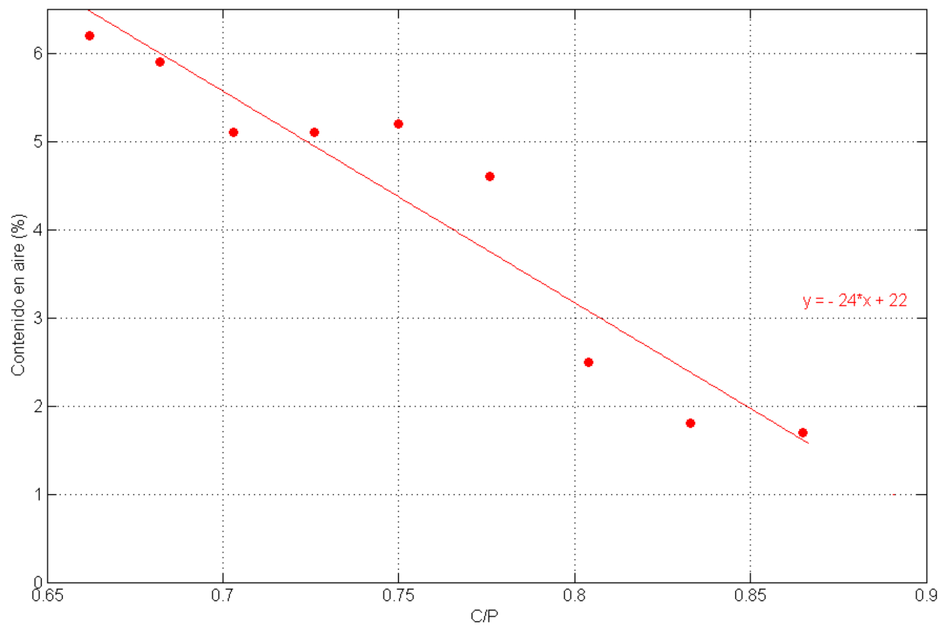


Figura E.9 Ensayos de contenido en aire del estudio paramétrico de cenizas volantes en SCM con SP Glenium 51

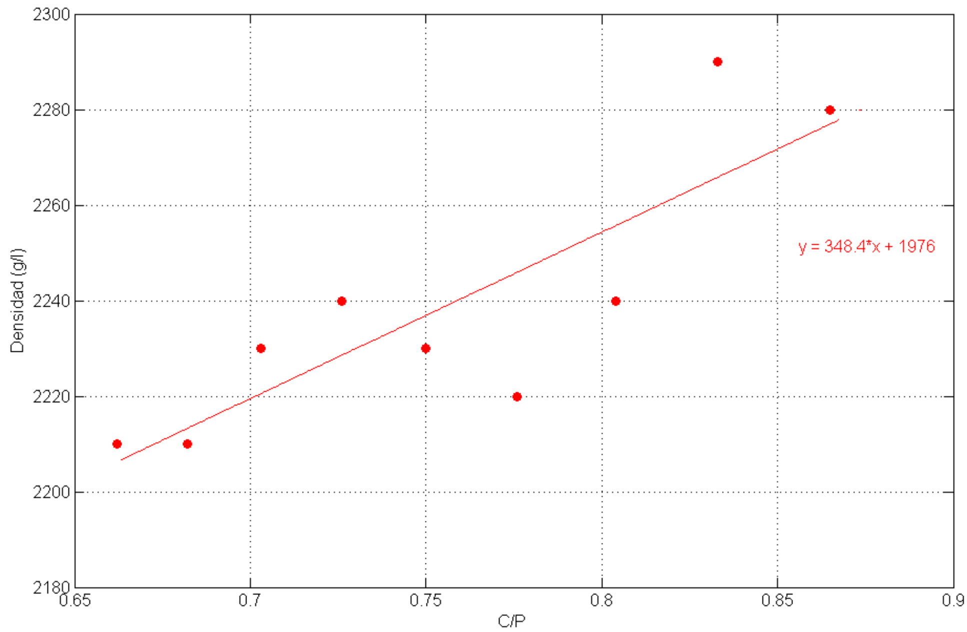


Figura E.10 Ensayos de densidad del estudio paramétrico de cenizas volantes en SCM con SP Glenium 51

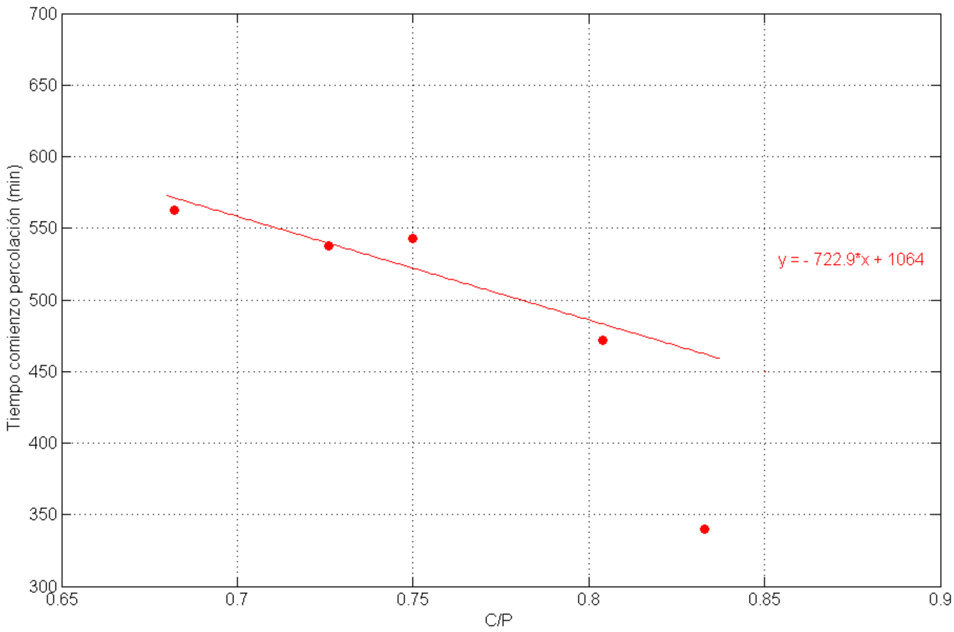


Figura E.11 Resultados del tiempo de comienzo de percolación con dispositivo de monitorización US del estudio paramétrico de cenizas volantes en SCM con SP Glenium 51

E.2.3 Influencia de la variación de la cantidad de Glenium 27

% SP (Glenium 27)	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
Slump flow 1a (mm)	100	100	101	157	200	214	247	266
Slump flow 1b (mm)	100	100	104	158	191	217	248	270
Slump flow 2a (mm)	100	100	102	160	172	209	238	257
Slump flow 2b (mm)	100	100	100	157	171	214	240	261
Slump flow 3a (mm)	100	100	108	145	190	219	260	267
Slump flow 3b (mm)	100	100	110	142	192	221	261	268
Media Slump flow (mm)	100	100	104	153	186	216	249	265
Flow 1a (mm)	144	163	176	221	245	246	268	281
Flow 1b (mm)	143	165	186	220	240	248	267	286
Flow 2a (mm)	147	161	186	218	222	250	257	271
Flow 2b (mm)	146	159	191	218	224	248	258	280
Flow 3a (mm)	154	164	183	215	248	263	281	279
Flow 3b (mm)	155	166	186	216	247	265	282	281
Media Flow (mm)	148	163	185	218	238	253	269	280
Contenido aire (% vol.)	5.4	5.2	4.75	4.75	4.3	4.6	3.7	4.5
Densidad (kg/m^3)	2200	2200	2220	2210	2210	2220	2230	2230
Tiempo comienzo percolación (min)	-	639	609	640	653	X	X	-

Tabla E. 3 Resultados del estudio paramétrico de la cantidad de SP Glenium 27 en SCM con cenizas volantes

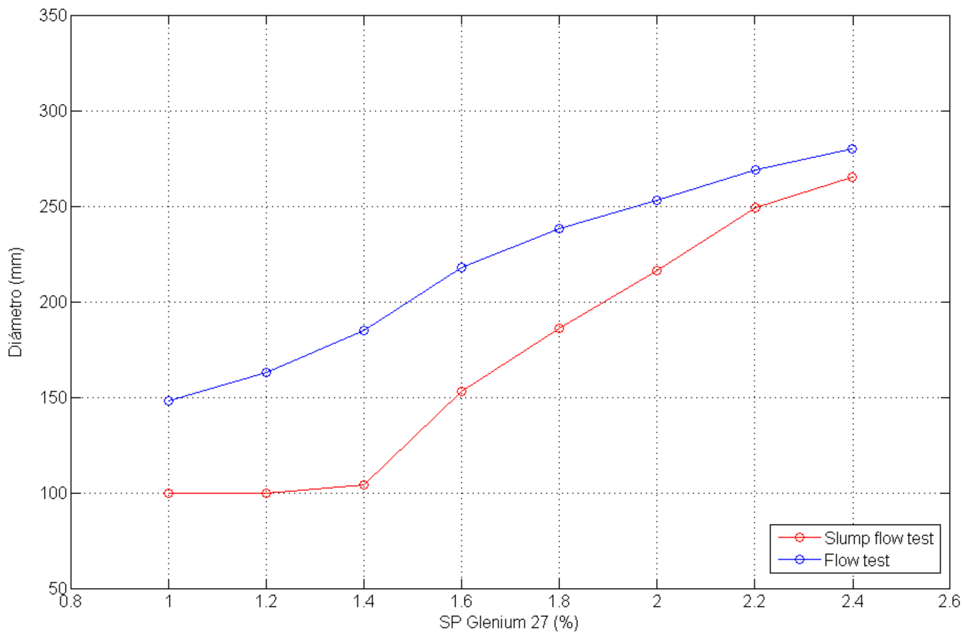


Figura E.12 Ensayos de fluidez del estudio paramétrico de la cantidad de SP Glenium 27 en SCM con cenizas volantes

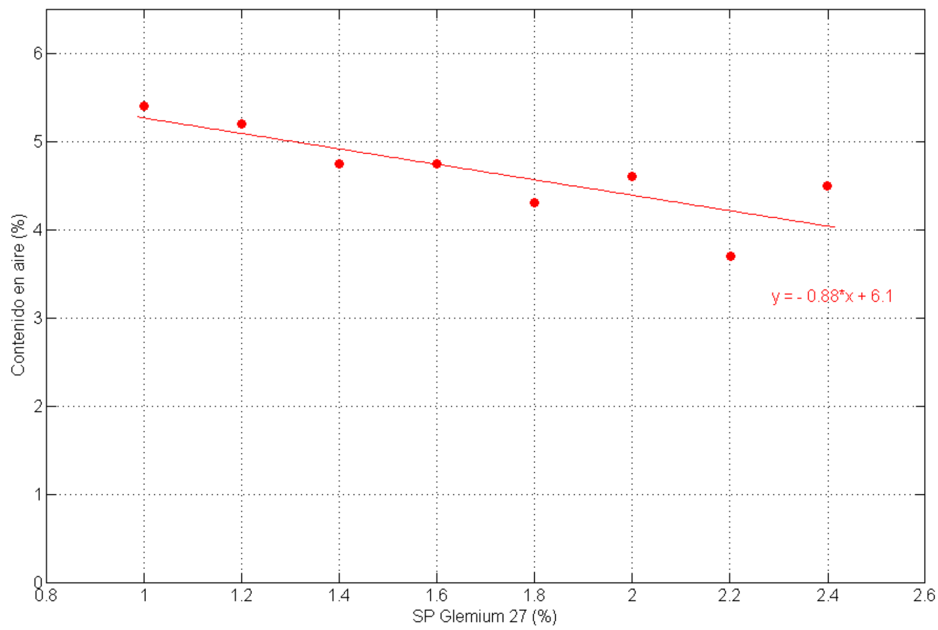


Figura E.13 Ensayos de contenido de aire del estudio paramétrico de la cantidad de SP Glenium 27 en SCM con cenizas volantes

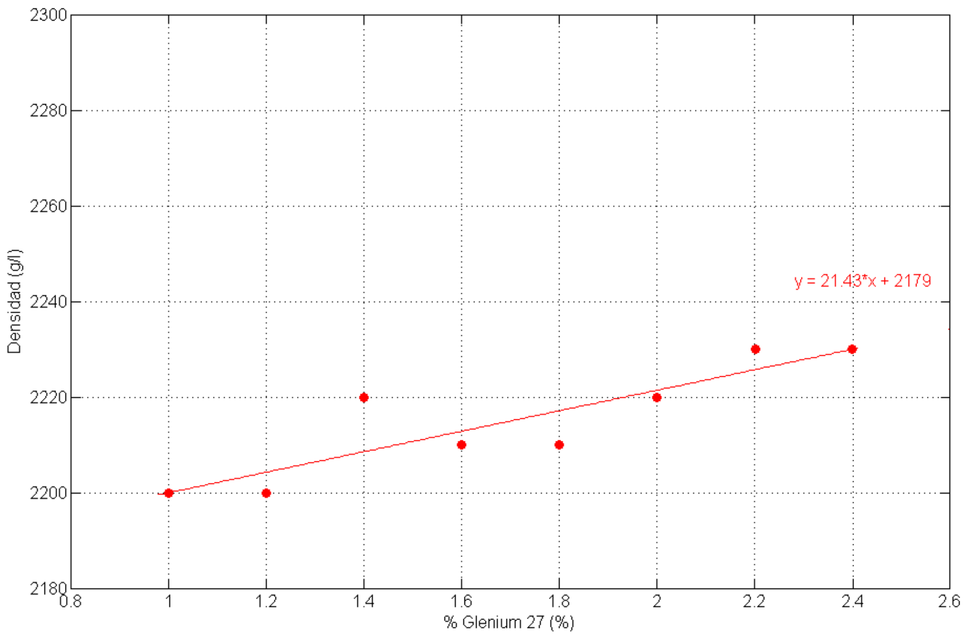


Figura E. 14 Ensayos de densidad del estudio paramétrico de la cantidad de SP Glenium 27 en SCM con cenizas volantes

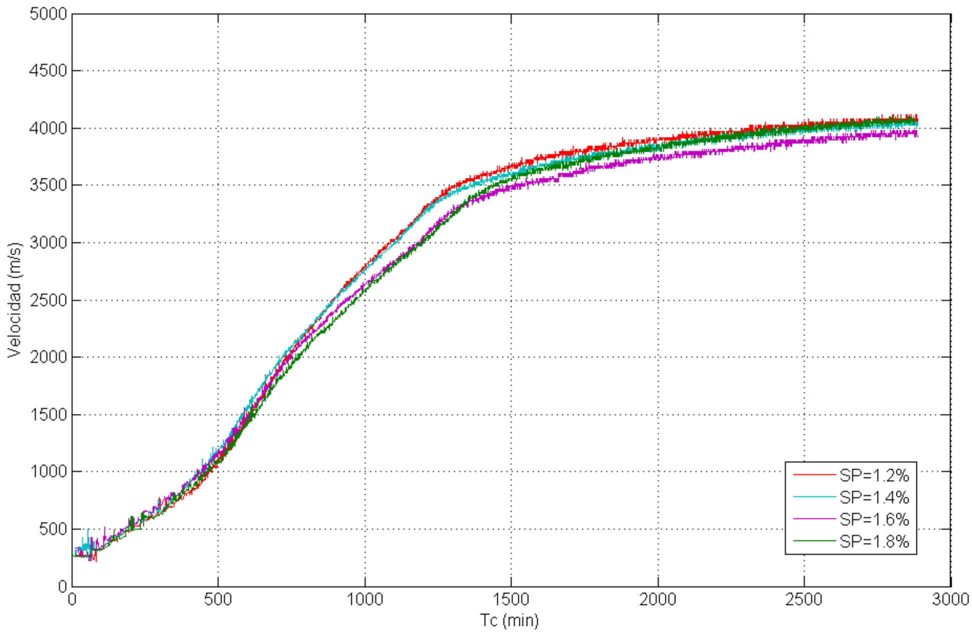


Figura E. 15 Resultados la curvas de velocidad obtenidas con el dispositivo de monitorización US del estudio paramétrico de la cantidad de SP Glenium 27 en SCM con cenizas volantes

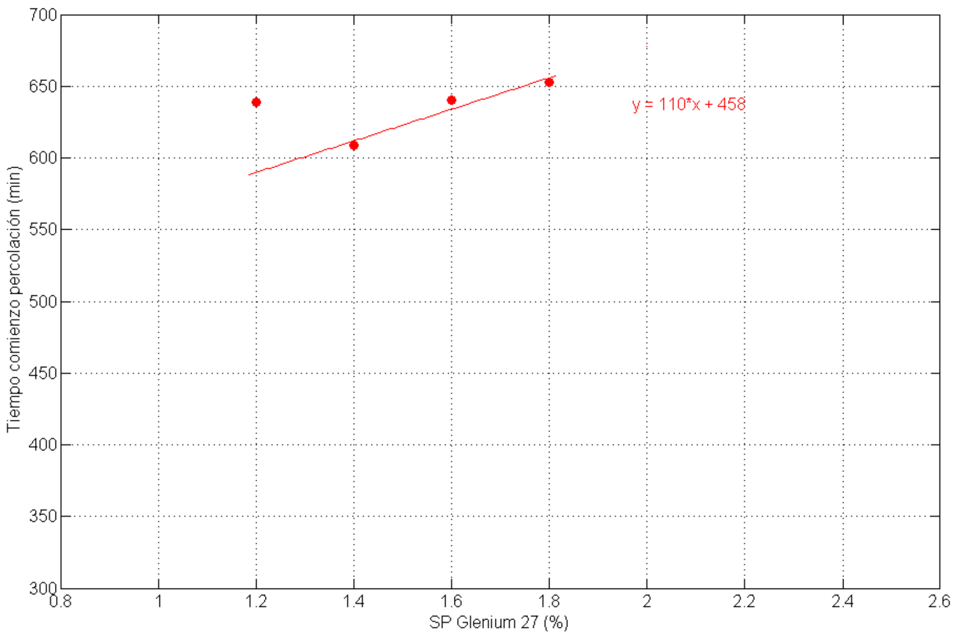


Figura E. 16 Resultados del tiempo de comienzo de percolación con dispositivo de monitorización US del estudio paramétrico de la cantidad de SP Glenium 27 en SCM con cenizas volantes

Anexo F

F. Código en Matlab para el tratamiento de datos

F.1 Freshcon data treatment

Este programa para Matlab es el encargado del tratamiento de datos automático de la señales recibidas por el dispositivo Freshcon.

```
%% 0. Initialization

clc
close all
clear all


%% 1. Test parameters

MaxAge=2880;            % Test duration (minutes)
fmax=1e6;               % Max. frequency to analyze (Hz)
fmin=610.346924;        % Min. frequency to analyze/frequency sample(Hz)
SN1=[0:MaxAge];               % Time configuration 1
%SN1=[0:0.25:99.75,100:0.5:299.5,300:1738,1739:5:2879,2880];  %Time
configuration 2
buf=1639;       % Number of time samples before the first positive one


%% 2. Analysis parameters

TH=0.1; % Amplitude threshold to determine the filter's cut-off
frequency
cs=1.2; % Security coefficient to determine the filter's cut-off
frequency
AI=1.2; % Allowed increment of the filter's cut-off frequency when the
            time decreases one minute
mixture =['C1-S1-240-F3-075'];   %Name of the mixture


%% 3. Additional parameters

nh=5;        % Number of rows to be skipped in frequency spectrum files
sm=round(fmax/fmin);      % Number of analyzed amplitude samples
SN=floor(SN1);
L=length(SN)-1;           % Number of recorded signals
S1=find(SN>=1);
s1=S1(1);                 % First sample after minute 0


%% 4.Preliminary filter's cut-off frequency calculation

for i=L:-1:s1
    if i>1000              %it reads frequency spectrum file
      fdata(1,:)=txt2mat(sprintf('fft/tst%d-Fft.dat',i-1),nh);
      else if i>100
       fdata(1,:)=txt2mat(sprintf('fft/tst0%d-Fft.dat',i-1),nh);
     else if i>10
      fdata(1,:)=txt2mat(sprintf('fft/tst00%d-Fft.dat',i-1),nh);
```

```
      else fdata(1,:)=txt2mat(sprintf('fft/tst000%d-Fft.dat',i-1),nh);
         end
      end
    end

    for j=1:sm        % the necesary part of the spectrum is selected
        Z(1,j)=fdata(1,j);
    end
    if max(Z(1,:))<0.0000000000001       % it is checked if the file
                                         isn't wrong
        ind(1)=0;
    else
      Zn(1,:)=Z(1,:)/max(Z(1,:));     % the spectrum is normalized
      ind=find(Zn>=TH);% the values bigger than a threshold TH
                        are detected
    end
    if ind(1)<1        % it is used to avoid problems with wrong files
        ind(1)=3200;
    else ind(1)=ind(1);
    end
    % cut-off frequency is calculated
    % Cut-off frequency= max(f(A>TH))*SecurityCoefficient
    cutfrec(SN(i))=ind(end)*fmin*cs;
end

cutfrec(MaxAge)=2000000;  % this value is a start reference to
                            calculate the first value

% if there is no signal every minute the cut-off frequency gaps are
filled with the precedent value
for i=2:MaxAge
    if cutfrec(i)<0.1
        cutfrec(i)=cutfrec(i-1);
    else cutfrec(i)=cutfrec(i);
    end
end


% Going from older to younger concrete the cut frequency is now
allowed to grow more than AI
for i=L:-1:s1
    if cutfrec(SN(i))<AI*cutfrec(SN(i)+1)
        cutfrec(SN(i))=cutfrec(SN(i));
        else cutfrec(SN(i))=cutfrec(SN(i)+1);
    end
end



%% 5. Smoothing of filter's cut-off frequency

fcut(:,1)=cutfrec;

for i=1:49          % the mean of the first 49 values is calculated
    fcut2(i,1)=sum(fcut(1:49,1))/49;
end
% each value is calculated by making the average with the 49 precedent
and the 49 following values
for i=50:MaxAge-49
```

```
    fcut2(i,1)=sum(fcut(i-49:i+49,1))/99;
end
for i=MaxAge-48:MaxAge  % the last 49 values aren't modified
    fcut2(i,1)=fcut(i,1);
end
%the filter's cut-off frequency is stored in a file
name=sprintf('Cutfreq-%s.dat',mixture);
DLMWRITE(name,fcut2,'delimiter','\t');

clear cutfrec;


%% 6. Limits selection to group

%if the calculation is stopped after this point, run cells 0,1,2 and 3
and restart here
cutfrec=txt2mat(name);
plot(1:MaxAge,cutfrec(1:MaxAge));

L1=50000;    %Frequency level 1 (Hz): For the small holder
                  cut freq(1/3*Tsop)
%Frequency level 1 (Hz): For the big holder cut freq(2/3*Tsop)
% If the cut frequency starts with a long flat zone (more than 90
minutes)the frequency level 2 should be slightly higher than this
constant cut-off frequency value
L2=20000;% Frequency level 2 (Hz):For the big holder
            cut freq(1/3*Tsop)
% Frequency level 2 (Hz):For the small holder cut freq (1/6*Tsop)

lw1=100;lw2=300;lw3=500; % For the big holder
%lw1=50;lw2=100;lw3=200;  % For the small holder
%it is found the last signal to be treated calculating the average
signal with 1 precedent and 1 following signals
indR1=find(cutfrec<=L1);sR1=find(SN<indR1(end));lR1=max(sR1);
%it is found the last signal to be treated calculating the average
signal with 3 precedent and 3 following signals
indR3=find(cutfrec<=(L1+L2)/2);sR3=find(SN<indR3(end));lR3=max(sR3);
%it is found the last signal to be treated calculating the average
signal with 5 precedent and 5 following signals
indR5=find(cutfrec<=L2);sR5=find(SN<indR5(end));lR5=max(sR5);



%% 7. Filtering of grouped signals

% Average signal with 1 precedent and 1 following signals
grouping(lR3+1,lR1,1);   % Average signals are calculated
for i=lR3+1:lR1
[B,data]=createfilter(i,cutfrec,SN);          % Filter is calculated
clear filtered;
sim('filtroBuenoVar.mdl');                    %Signal is filtered
% Signal is cut and the delay calculated
fdelay(i,1)=postfilter(filtered,data,i,lw1,500,3000,buf);
end
% Delay is stored in a file
name=sprintf('Delay-%s.dat',mixture);
DLMWRITE(name,fdelay,'delimiter','\t');

% Average signal with 3 precedent and 3 following signals
```

```
grouping(lR5+1,lR3,3);
for i=lR5+1:lR3
[B,data]=createfilter(i,cutfrec,SN);
clear filtered;
sim('filtroBuenoVar.mdl');
fdelay(i,1)=postfilter(filtered,data,i,lw2,500,4500,buf);
end
name=sprintf('Delay-%s.dat',mixture);
DLMWRITE(name,fdelay,'delimiter','\t');

% Average signal with 5 precedent and 5 following signals
grouping(max(s1,6),lR5,5);
for i=max(s1,6):lR5
[B,data]=createfilter(i,cutfrec,SN);
clear filtered;
sim('filtroBuenoVar.mdl');
fdelay(i,1)=postfilter(filtered,data,i,lw3,500,4500,buf);
end
name=sprintf('Delay-%s.dat',mixture);
DLMWRITE(name,fdelay,'delimiter','\t');



%% 8. Filtering of non grouped signals

for i=lR1:99 %Signals between the last grouped signal and 99

data=txt2mat(sprintf('RAW DATA/tst00%d.dat',i)); %The signal is read
data(:,2)=detrend(data(:,2)); %Freshcon amplitude's signal mean is
removed
[numB,denB ] = besself(1,cutfrec(SN(i+1))*2*3.141592);
Bc=tf(numB,denB);
B=c2d(Bc,0.1e-6,'Tustin');  %Discrete filter is calculated
sim('filtroBuenoVar.mdl');  %Signal is filtered
%Signal is cut, delay is calculated
fdelay(i,1)=postfilter(filtered,data,i,lw1,500,3000,buf);

end


mx=max(100,lR1);

for i=mx:999   %Signals between the last grouped signal or 100 and 999

data=txt2mat(sprintf('RAW DATA/tst0%d.dat',i));
data(:,2)=detrend(data(:,2));
[numB,denB ] = besself(1,cutfrec(SN(i+1))*2*3.141592);
Bc=tf(numB,denB);
B=c2d(Bc,0.1e-6,'Tustin');
sim('filtroBuenoVar.mdl');
fdelay(i,1)=postfilter(filtered,data,i,lw1,500,3000,buf);

end


mx=max(1000,lR1);

for i=1000:L-1    %Signal number bigger than the last grouped signal
```

```
                   or 1000 and 999

data=txt2mat(sprintf('RAW DATA/tst%d.dat',i));
data(:,2)=detrend(data(:,2));
[numB,denB ] = besself(1,cutfrec(SN(i+1))*2*3.141592);
Bc=tf(numB,denB);
B=c2d(Bc,0.1e-6,'Tustin');
sim('filtroBuenoVar.mdl');
fdelay(i,1)=postfilter(filtered,data,i,lw1,500,3000,buf);

end

% Delay is stored in a file
name=sprintf('Delay-%s.dat',mixture);
DLMWRITE(name,fdelay,'delimiter','\t');


%% 9. Replacement of'.' by ','

%Use MFAR software


%% 10. Preliminary velocity curve calculation

%Use Frehcon offline software

%A velocity file is obtained


%% 11. Final curve calculation

DX=57.1e-3;             %Real distance of the mortar sample
DXFC=59e-3;           %Default distance in Freshcon setting
timedelay=6;          %time between the addition of water and the start
                         of the test
%Speed is read from the file created by Freshcon offline
nh=2;
file=txt2mat('filtered-VE.dat',nh);
speed(:,1)=file(:,2);
%Delay is read from the file created before
name=sprintf('Delay-%s.dat',mixture);
delay(:,1)=txt2mat(name);
%time is determined by time configuration
time(:,1)=SN1(1:end-1);
% In case of not having a signal every minute is necesary to compress
the delay values
searchgap=find(delay(:,1)>0);
delay2(1:length(searchgap),1)=delay(searchgap(1:end));
%the speed calculated by Freshcon offline is corrected substracting
the delay time and correcting the value of the real distance
for i=1:length(searchgap)
speed2(i,1)=DXFC/((DXFC/speed(i,1))-delay2(i)*1e-7)*DX/DXFC;
end
%The final file is composed by 4 columns
file2(:,1)=time(max(s1,6)+1:end,1)+timedelay; %column 1: time
file2(:,2)=speed(:,1);                        %column 2: preliminary
speed
file2(:,3)=delay(max(s1,6):end,1);            %column 3: delay
```

```
file2(:,4)=speed2(:,1);                        %column 4: corrected
speed
%the file is stored
name=sprintf('Speed-%s.dat',mixture);
DLMWRITE(name,file2,'delimiter','\t');


%% 12. Manual cleaning

%Eliminate peaks in the created file
plot(file2(:,1),file2(:,4));grid on;
%the file is stored
name=sprintf('Speed-%s.dat',mixture);
DLMWRITE(name,file2,'delimiter','\t');
```

F.2 Grouping

Esta función implementada en el programa *Freshcon data treatment* se encarga de calcular la señal media de 2R+1 señales para las señales comprendidas entre LS y HS.

```
function grouping(LS,HS,R)
%LS Number of the first signal to group
%HS Number of the last sample to group
%R Number of precedent and following signals used to calculate the
average signal

for i=LS-R:HS+R

   if i<10       %All the needed signals  are read
       data=txt2mat(sprintf('RAW DATA/tst000%d.dat',i));
   else if i<100
           data=txt2mat(sprintf('RAW DATA/tst00%d.dat',i));
       else if i<1000
            data=txt2mat(sprintf('RAW DATA/tst0%d.dat',i));
           else
               data=txt2mat(sprintf('RAW DATA/tst%d.dat',i));
           end
       end
   end

   %data is a 2-column matrix
   %1st column contain time values in s
   %2nd column contain amplitude values in V

   Alldata(:,i)=data(:,2); %All the signals' amplitudes are stored in
                                columns
end

for i=LS:HS
    % the average of 2R+1 signals is calculated
    mean=Alldata(:,i-R);
    for k=1:2*R
        mean=mean+Alldata(:,i-R+k);
    end
    mean=mean/(2*R+1);
```

```
    % the average amplitude of the signals is recorded in data matrix
    data(:,2)=mean;
    %the data matrix is saved in a file
    if i<10
       savefile=sprintf('GROUPED DATA/grouped000%d.dat',i);
        else if i<100
           savefile=sprintf('GROUPED DATA/grouped00%d.dat',i);
            else if i<1000
                savefile=sprintf('GROUPED DATA/grouped0%d.dat',i);
                else
                    savefile=sprintf('GROUPED DATA/grouped%d.dat',i);
                end
            end
        end
    DLMWRITE(savefile,data,'delimiter','\t','precision','%.7f');
    i %it shows the progress of the function
end
```

F.3 Createfilter

Esta función implementada en el programa *Freshcon data treatment* lee la señal a filtrar y calcula la función de transferencia a implementar en el filtro Bessel.

```
function [B,data]=createfilter(S,cutfrec,KN)

%S is the number of signal
%cutfrec is the profile of the  filter's cut-off frequency
%KN is the time configuration of the signals

% the continous Bessel filter is calculated
[numB,denB ] = besself(1,cutfrec(KN(S+1))*2*3.141592);
Bc=tf(numB,denB);
%the continous filter is discretized
B=c2d(Bc,0.1e-6,'Tustin');

%Freshcon data is loaded
if S<10
     data=txt2mat(sprintf('GROUPED DATA/grouped000%d.dat',S));
    else if S<100
      data=txt2mat(sprintf('GROUPED DATA/grouped00%d.dat',S));
         else if S<1000
             data=txt2mat(sprintf('GROUPED DATA/grouped0%d.dat',S));
              else
                data=txt2mat(sprintf('GROUPED DATA/grouped%d.dat',S));
              end
          end
    end

%Freshcon amplitude's signal mean is removed
data(:,2)=detrend(data(:,2));
```

F.4 Postfilter

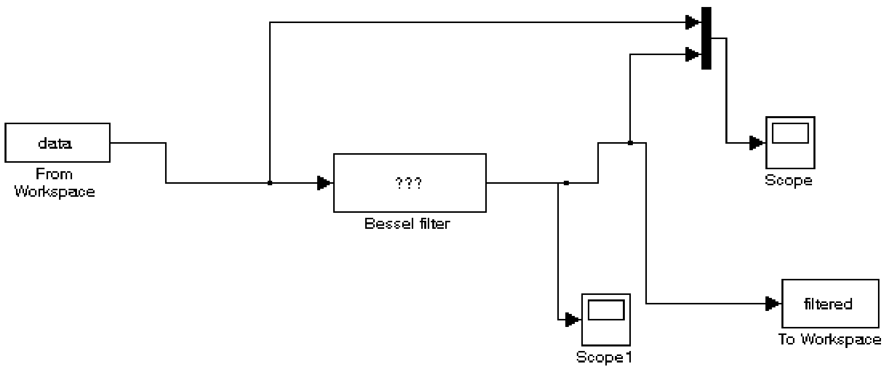
Esta función está implementada en el programa *Freshcon data treatment* y trata las señales después de ser filtradas.

```
function delay=postfilter(filtered,data,S,lw,hw,sz,buf)

%data is the signal recorded by Freshcon
%filtered is the signal filtered by the Bessel filter
%S is the number of the analyzed signal
%lw is the number of samples progressively attenuated at the beginning
%hw is the number of samples progressively attenuated at the end
%sz is desired size in samples of the processed signal
%buf is the number of time samples stored before the first positive
one

clear delay;
clear   c mx a;
%Cross correlation of the original and the filtered signal is
performed
a=size(data(:,2));
c=xcorr(filtered(1:a(1)),data(:,2));
%the delay is  the time where the maximum of the  cross correlation
%function is located
mx=max(c);
if mx<0.000000000000001
    delay=0;
else delay=find(c>=mx)-a(1);
end
%it shows the progress of the aplication
S+1
delay
clear   filtered2 ;

%the first lw samples (starting from time 0) are attenuated by a
factor increasing linearly from 0 to 1
for k=1:lw-1
    filtered2(k,2)=filtered(buf+k,1)*k/lw;
    filtered2(k,1)=0.0000001*k;
end
for k=lw:sz-hw
    filtered2(k,2)=filtered(k+buf,1);
    filtered2(k,1)=0.0000001*k;
end
%the last hw samples are attenuated by a factor decreasing linearly
from 1 to 0
for k=sz-hw+1:sz
    filtered2(k,2)=filtered(buf+k,1)*(sz-k)/hw;
    filtered2(k,1)=0.0000001*k;
end
%the treated signal is saved in a file
if S<10
     savefile=sprintf('TREATED DATA/filtered000%d.dat',S);
     else if S<100
      savefile=sprintf('TREATED DATA/filtered00%d.dat',S);
         else if S<1000
             savefile=sprintf('TREATED DATA/filtered0%d.dat',S);
```

```
                else
                   savefile=sprintf('TREATED DATA/filtered%d.dat',S);
                end
            end
      end


DLMWRITE(savefile,filtered2,'delimiter','\t','precision','%.7f');
end
```

F.5 Modelo de filtro Bessel

Este modelo en Simulink está implementado en programa *Freshcon data treatment* y es un modelo discretizado de filtro Bessel que filtra las señales discretas compuesta u originales almacenadas en el Workspace de Matlab, y vuelca también las señales filtradas al mismo Workspace.



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