Advanced ultrasonic techniques to characterize changes in microstructure due to carbonation and microcracking

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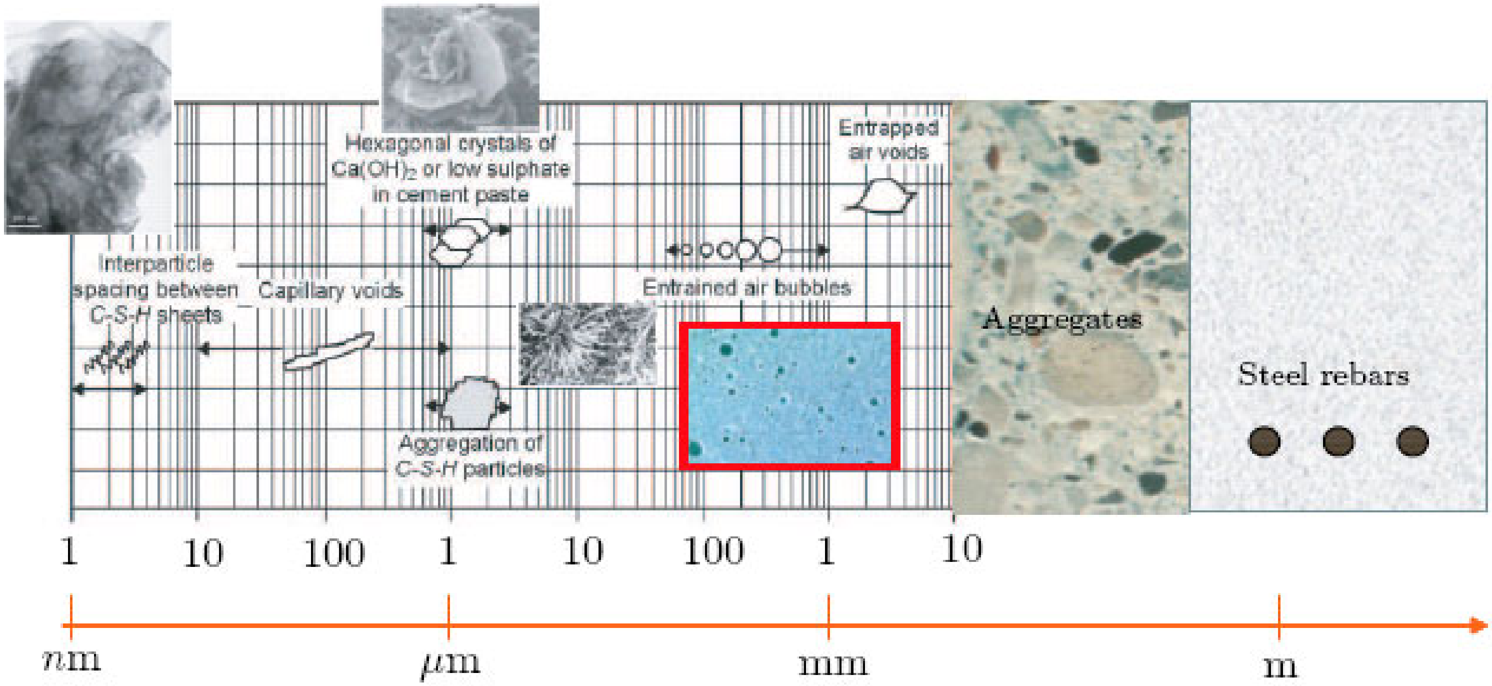
Rationale for advanced ultrasonic techniques

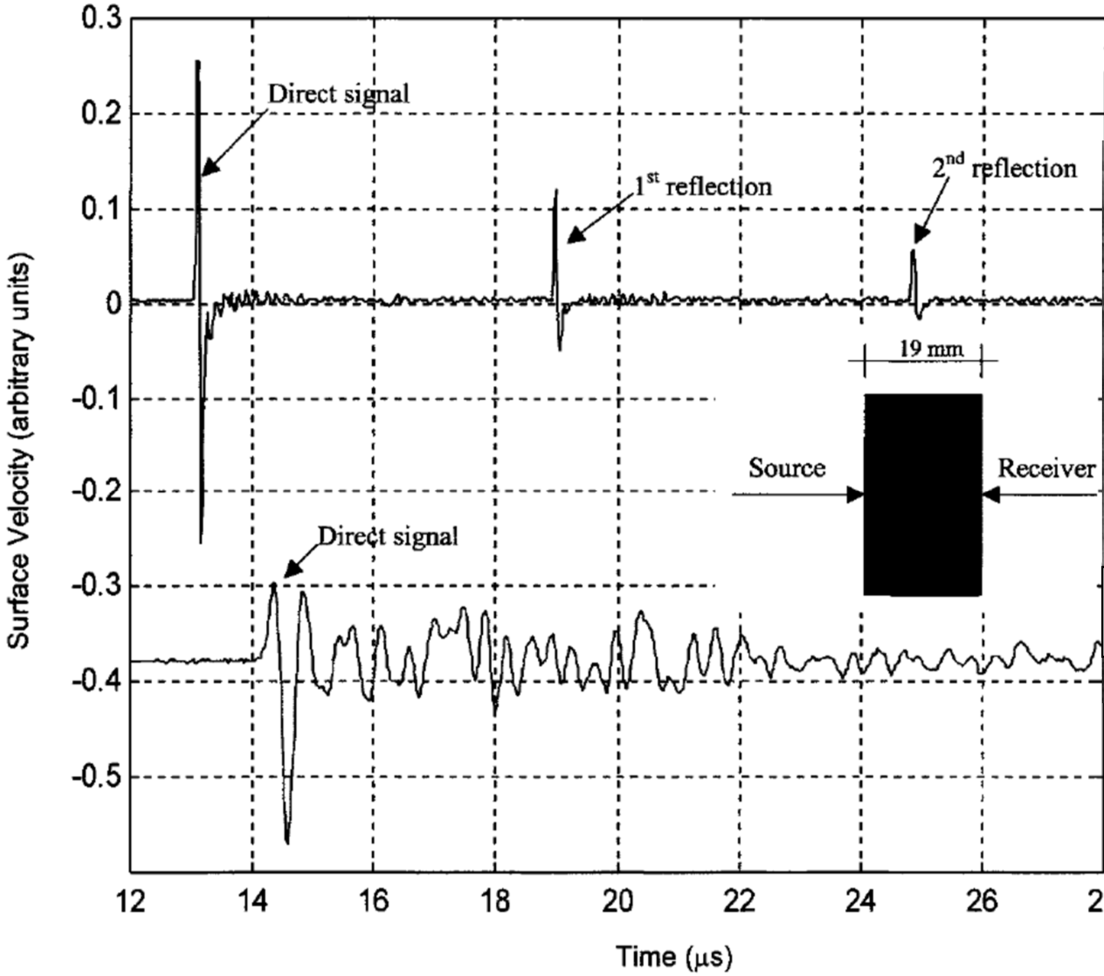


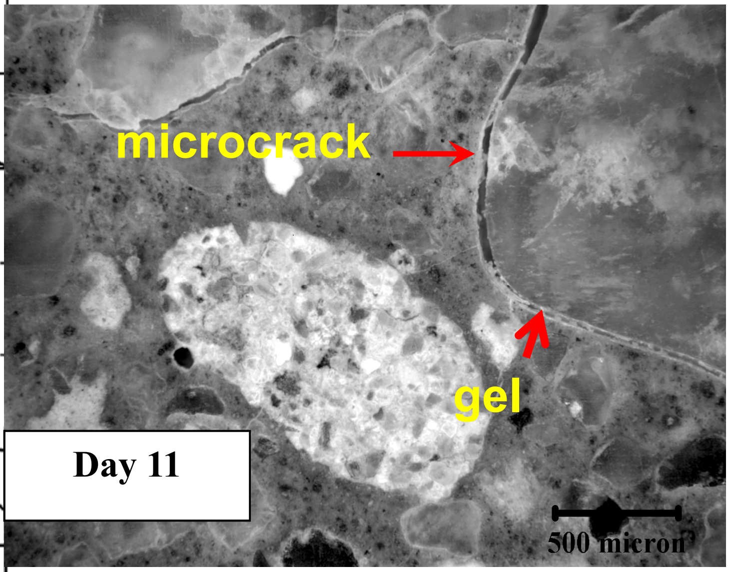
- Multi length scale, multiphase and heterogeneous
- Ultrasonic waves exhibit high attenuation (mainly scattering)
- Defects are on the order of the scatterers
- Immense scale and volume of concrete infrastructure

Reference: Mehta, PK. and Monteiro. PJM. Concrete: microstructure, properties, and materials, third edition. New York: McGraw Hall, 2006.

Inherent complexity of ultrasound in concrete

Inherent nonlinearity in microstructure plus hysteresis ASR damage





Basics of ultrasonic imaging and characterization

Linear Ultrasound

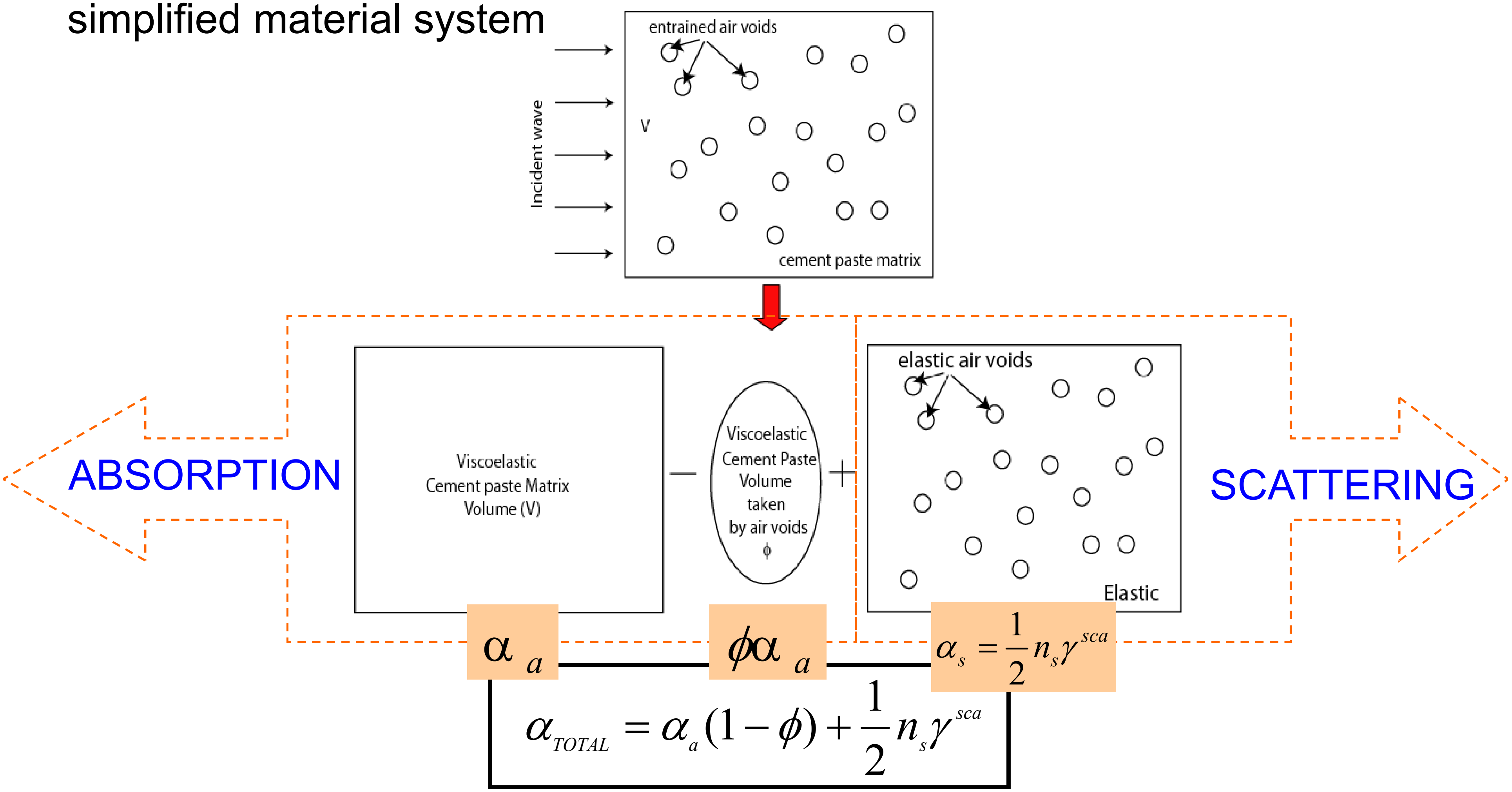
- Imagining is only possible if wavelength is on the order of the defect
- Linear ultrasonic parameters such as wave velocity (UPV), attenuation and dispersion are sensitive to linear elastic constants and density
- Low sensitivity to microscale defects and changes in microstructure
- Limited capability for the early evaluation of damage state

Nonlinear Ultrasound (NLU)

- Wavelength invariant
- Nonlinear ultrasonic parameters such as the acoustic nonlinearity parameter, β
- Are sensitive to nonlinear material properties
- Demonstrated sensitivity to early onset of nano- and microscale damage

Characterization with linear ultrasound

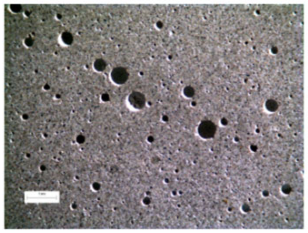
Analytical model of ultrasonic wave attenuation in a simplified material system



$$\alpha_{TOTAL} = \alpha_a(1-\phi) + \frac{1}{2} n_s \gamma^{sca}$$

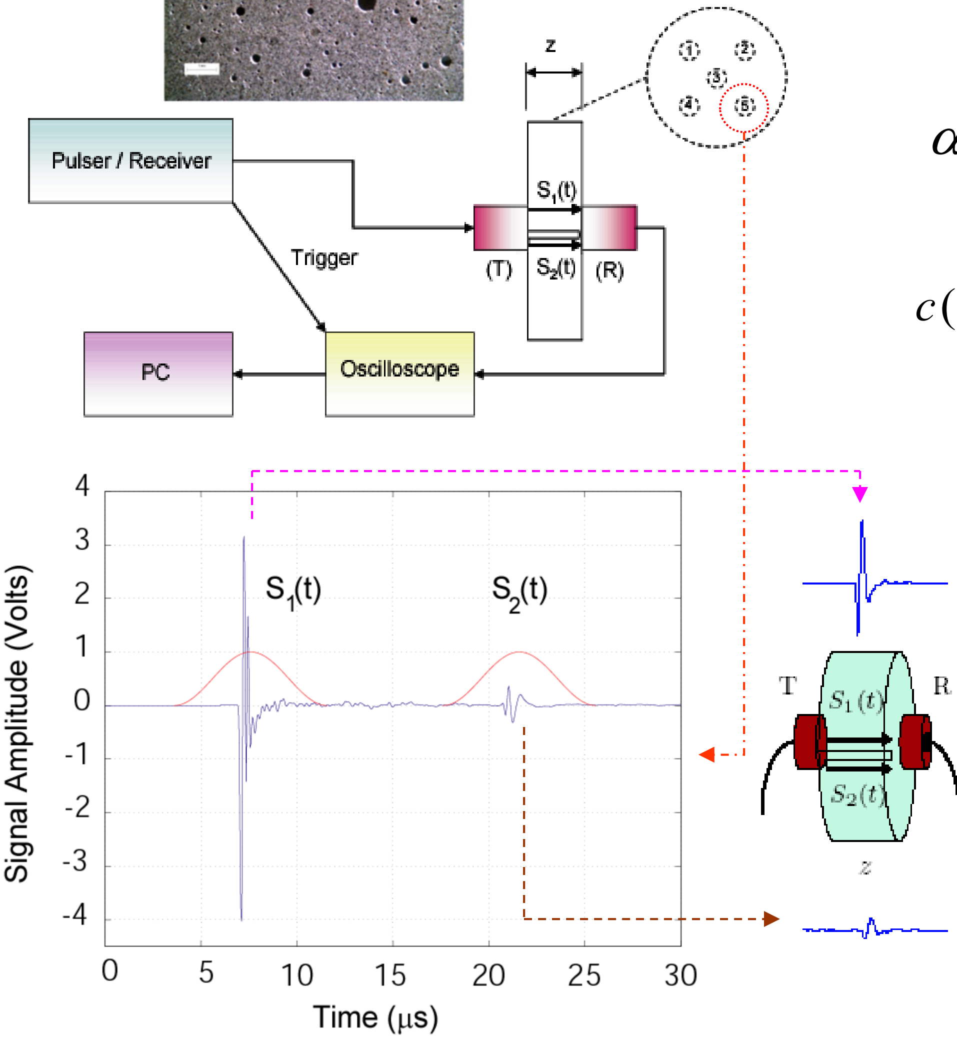
Reference: Biwa, S. Mechanics of Materials 33 (2001), 635-647.

Are quantitative linear ultrasonic measurements in concrete possible?



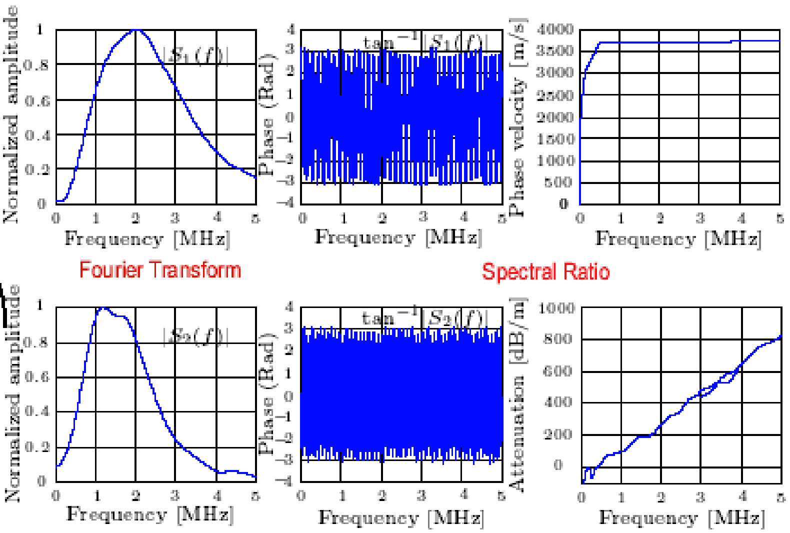
Scattering by entrained air voids

No coarse aggregate

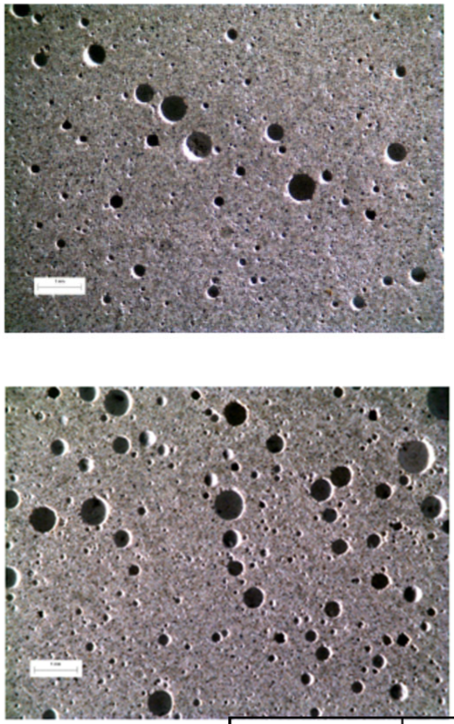


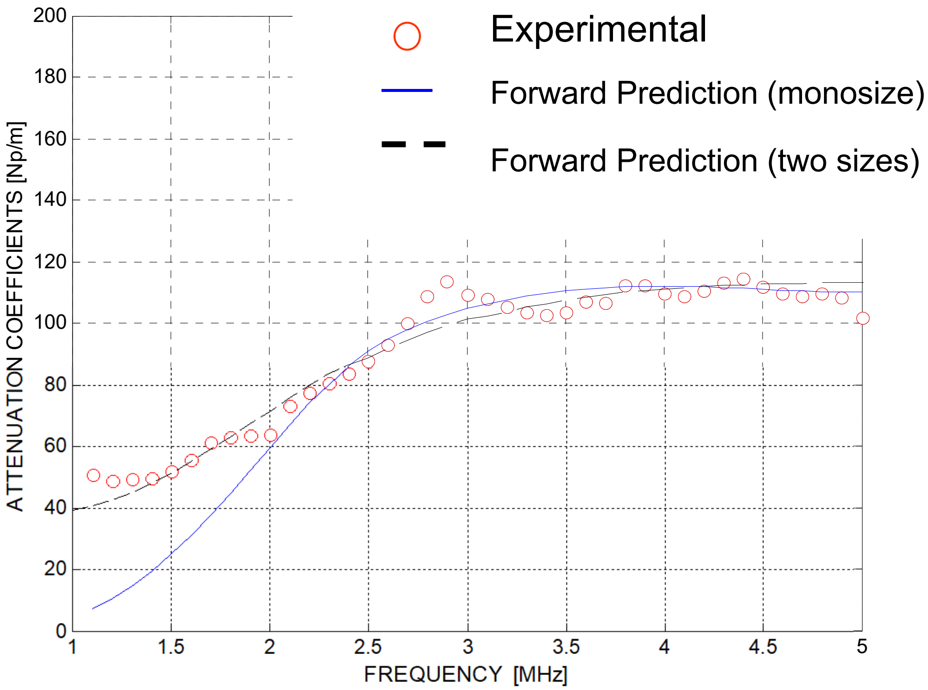
$$\alpha(f) = \frac{1}{2z}\left[\ln\left[\frac{S_1(f)}{S_2(f)}\right] - \ln\left[\frac{D_L(z)}{D_L(3z)}\right]\right]$$

$$c(f) = \frac{4\pi f z}{\arg\left[\frac{S_1(f)}{S_2(f)}\right] + \delta\phi}$$



Inversion is possible in simplified material





Name	Volume Fraction, ϕ (%)			Radius, a (mm)	
	ASTMC457-98 (Method B)	Simplex Prediction	% Difference	Simplex Prediction	Optical Reading
EACP1	4.1	3.3	19.5	0.33	0.32
EACP2	8.1	7	13.5	0.35	0.36
EACP3	12.2	11.3	7.4	0.5	0.49

Punurai, Jarzynski, Qu, Kim, Jacobs, Kurtis, Cement and Concrete Research (37) 2007

Basics of nonlinear ultrasound

Equation of motion (1D)

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma_{xx}}{\partial x}$$

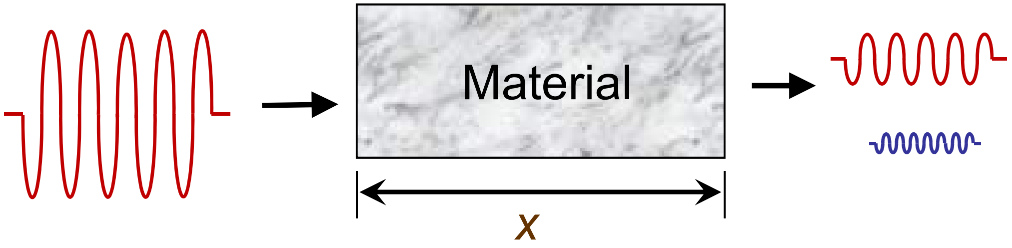
Nonlinear constitutive relationship

$$\sigma = \varepsilon \cdot E_0 \left[\ 1 + \beta\varepsilon + \delta\varepsilon^2 + \alpha\left(\Delta\varepsilon + \varepsilon \cdot \mathrm{sgn}\left(\dot{\varepsilon}\right)\right)\ \right]$$

---

u_{in} =

$A_o \sin(\omega t)$



u_{out} =

$A_1 \sin(\omega t\text{-}kx)$ +

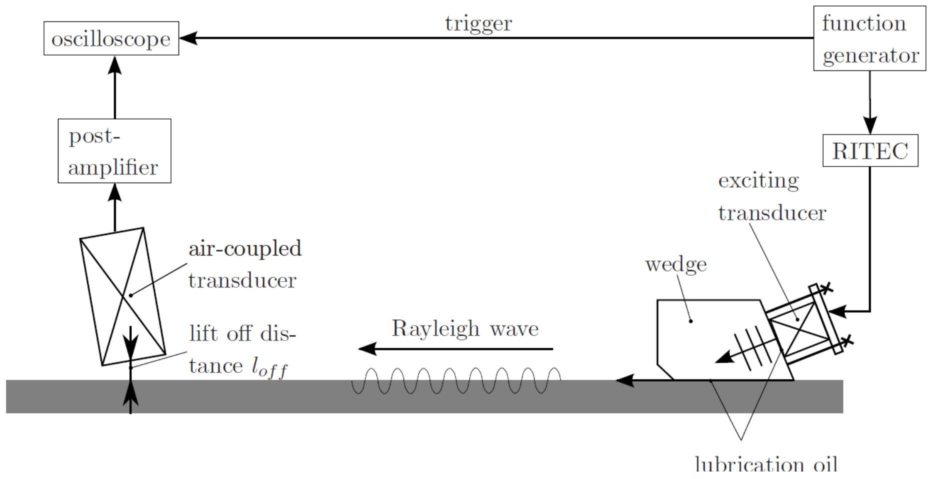
$A_2 \sin[2(\omega t\text{-}kx)]$

Acoustic Nonlinearity Parameter, β

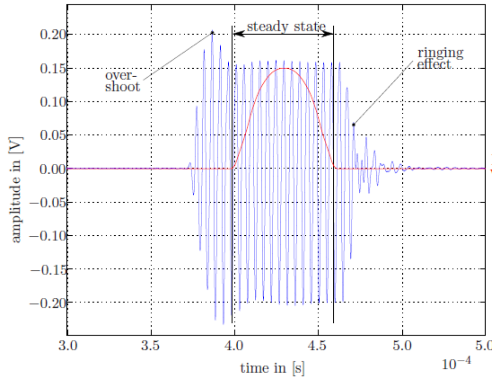
$$\boxed{A_2 = \frac{\beta A_1^2 x \kappa^2}{8}} \Rightarrow \boxed{\beta = \frac{A_2}{A_1^2}\left(\frac{8}{\kappa^2 x}\right)}$$

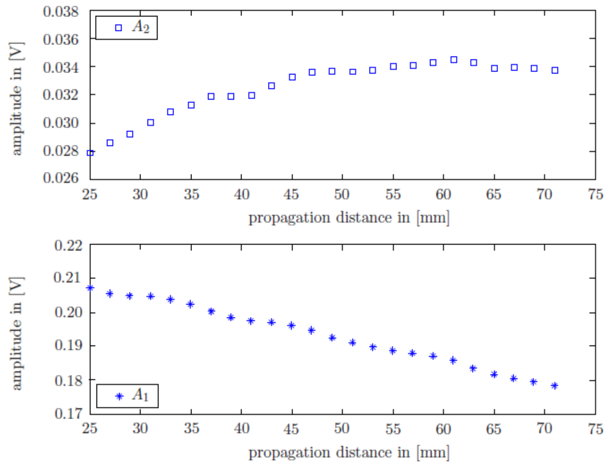
Nonlinear Rayleigh wave measurements

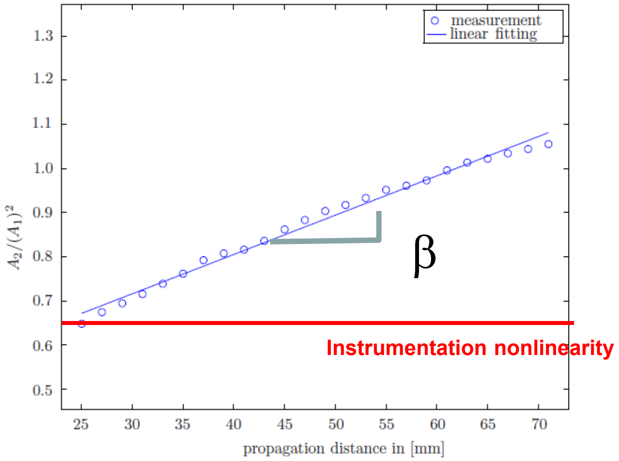
Non-contact detection of Rayleigh surface waves with an air-coupled receiver – material nonlinearity cumulative



- Isolate *material* nonlinearity from *instrumentation* nonlinearity
- Relative value of β
- $(A_2 / A_1^2) \propto \beta x$

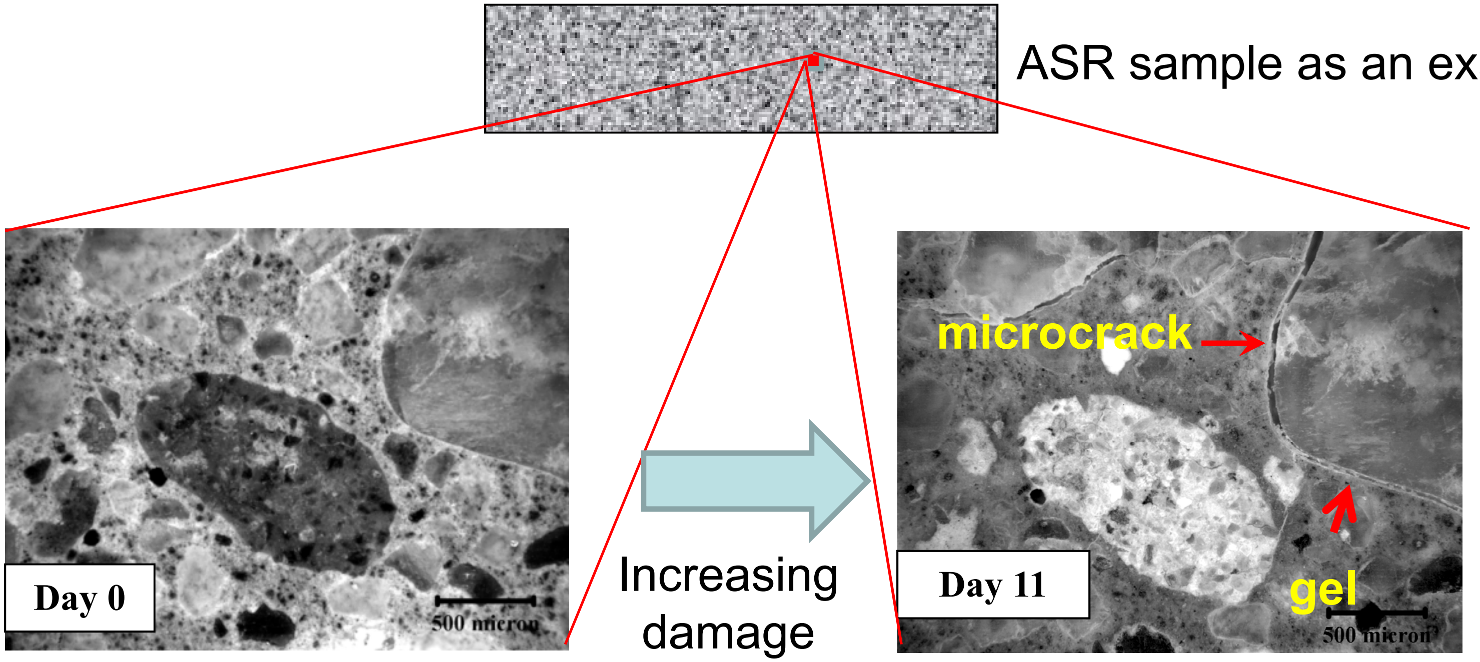






Nonlinear ultrasonic methods for concrete

Inherent nonlinearity in microstructure plus hysteresis type damage

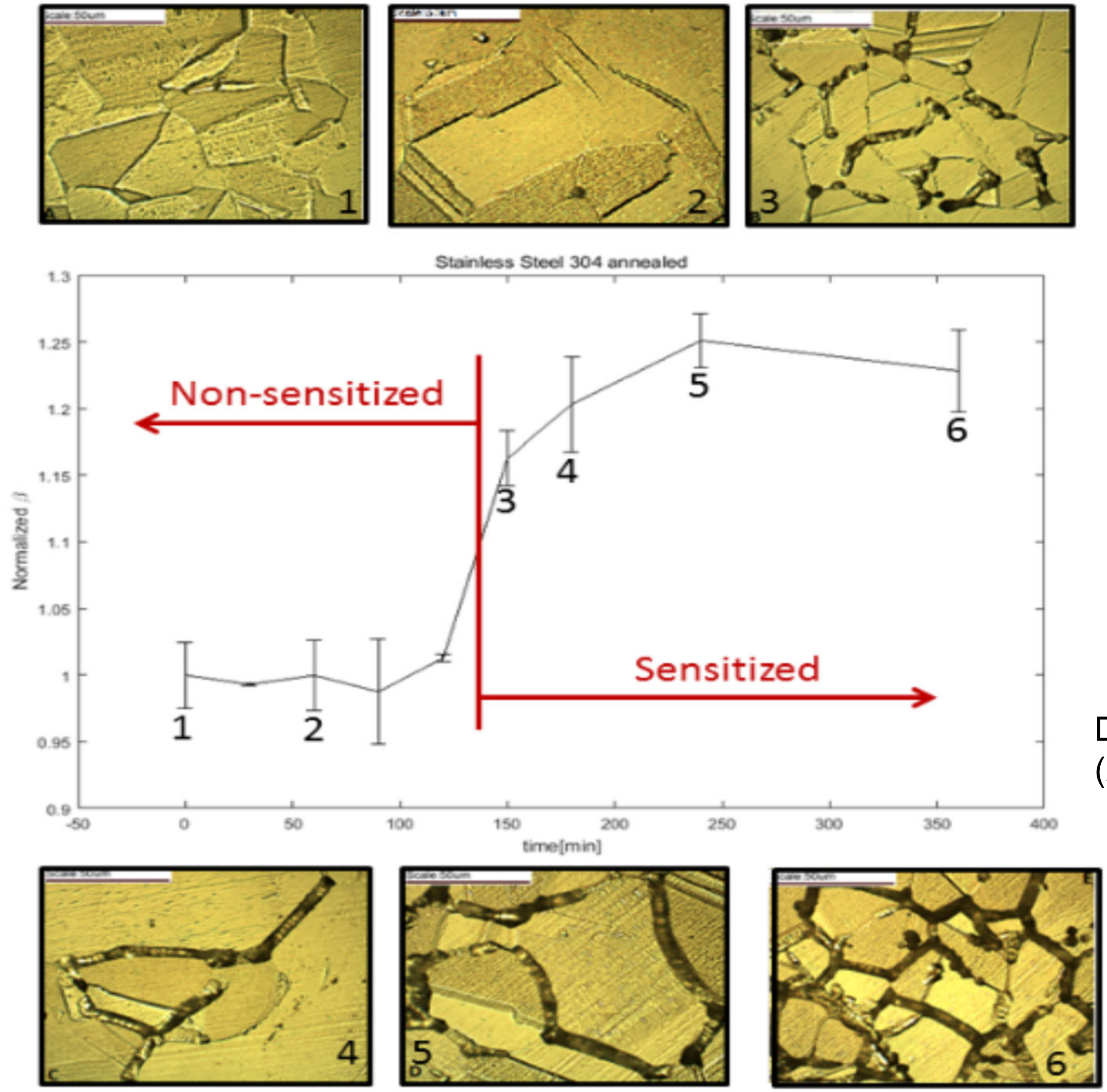


ASR sample as an example

Hard aggregate and soft matrix
Imperfect bonding (ITZ)
Porosity
Inherently nonlinear

Microcracks (in the ITZ, aggregate, paste)
ASR gel
Becomes more nonlinear with ASR damage
Due to the increased amount of the soft portion or the amount of damage (microcracks)

Sensitization 304 stainless steel



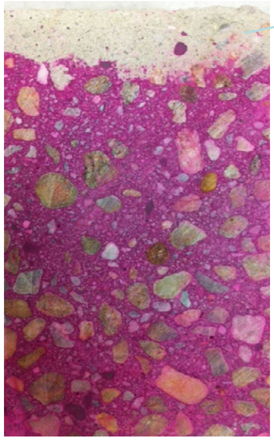
Doerr et al *NDT&E* , (2017)

Carbonation specimens

Accelerated test: Concrete blocks were placed in an environmental chamber (with a high CO_2 content) for 40 days

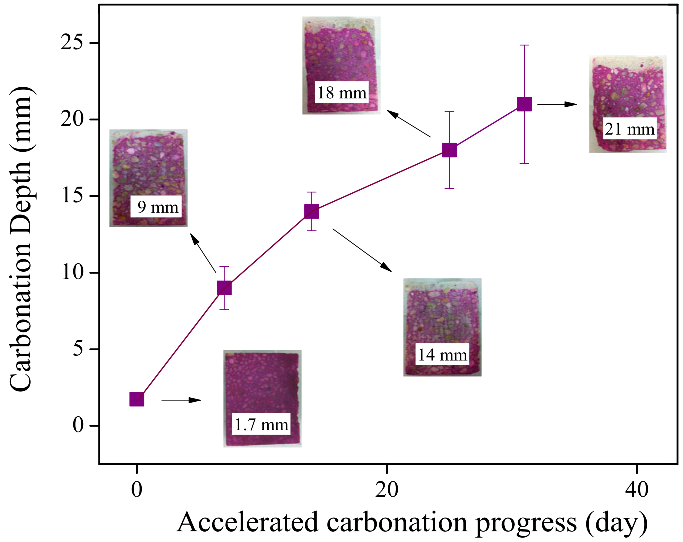
Destructive test: phenolphthalein spray on cut surface

Carbonation front after 31 days



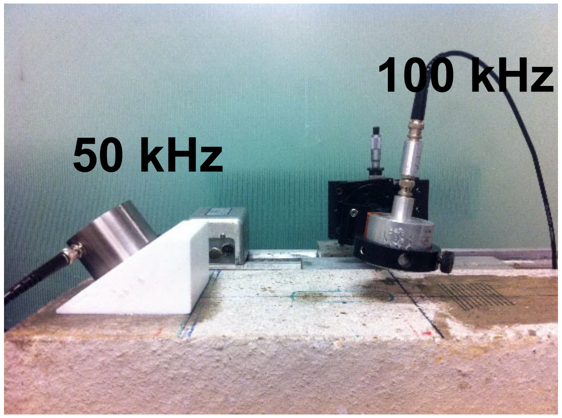
Carbonated area

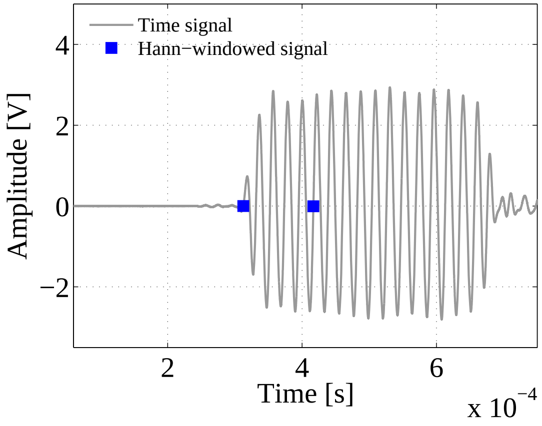
λ_{100kHz}=27 mm

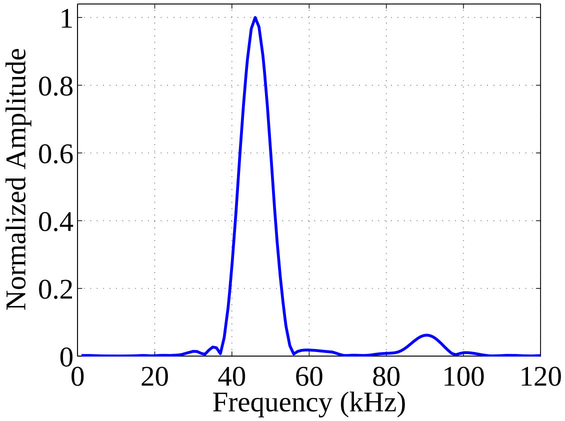


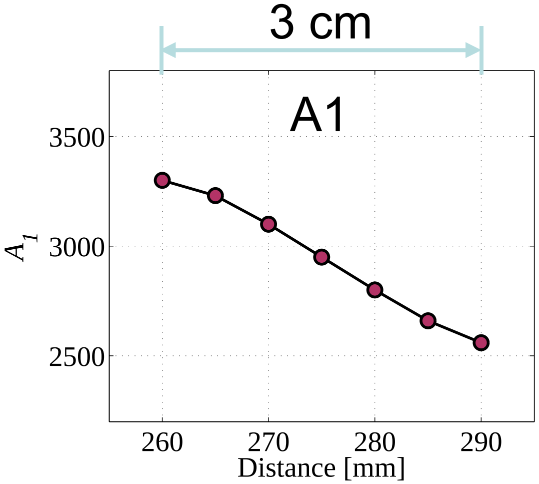
Nonlinear ultrasonic measurements

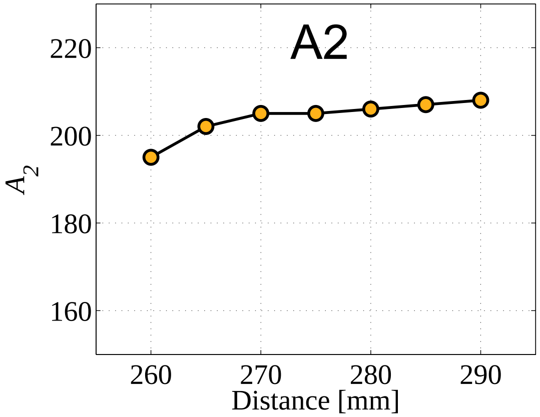
- Nonlinear Ultrasonic Measurement

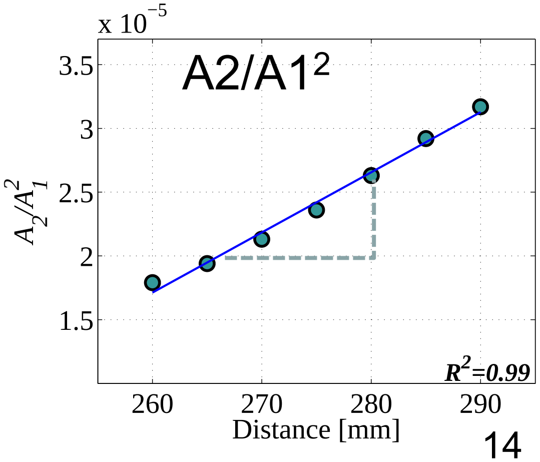




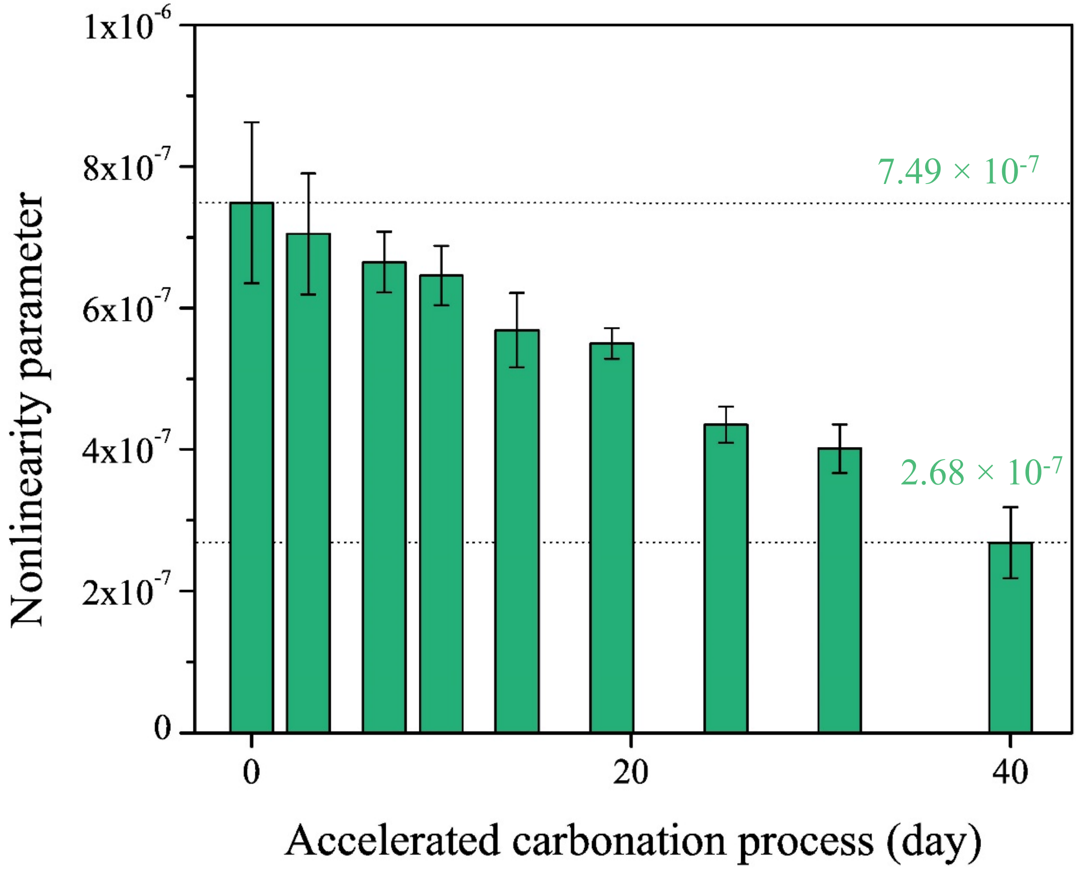








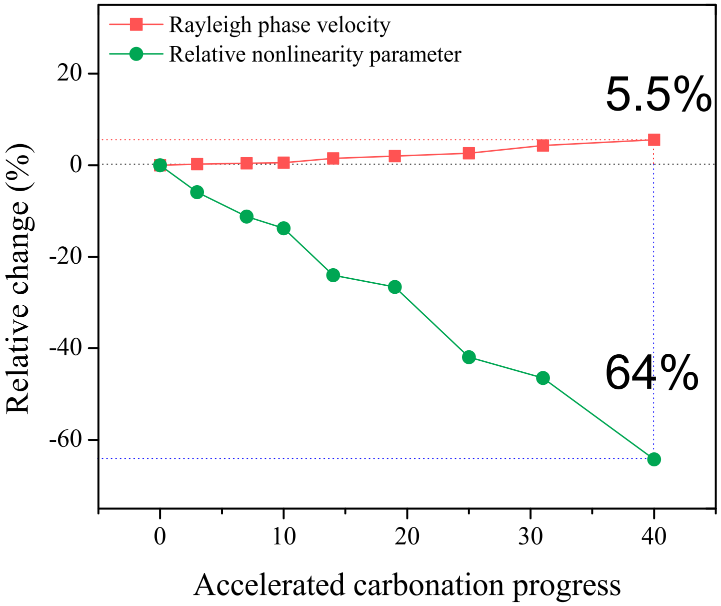
Sensitivity of nonlinearity β parameter to carbonation



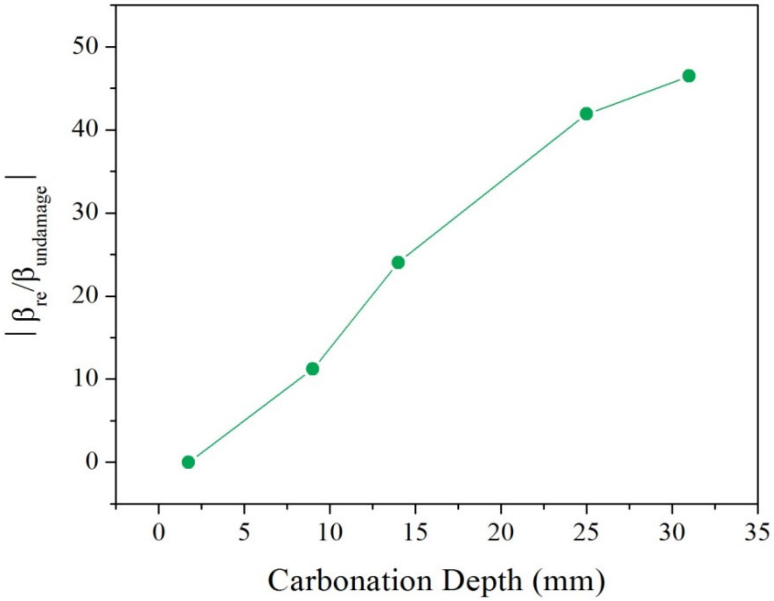
- Decrease in measured nonlinearity parameter due to changes in elastic modulus, density and the existing microcracks filled by the $CaCO_3$.

Nonlinear versus linear ultrasound

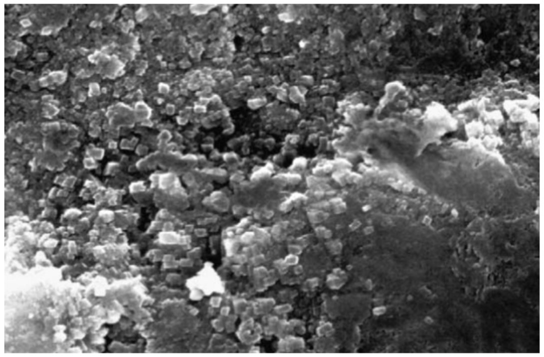
Nonlinearity parameter, Wave speed



Depth – Nonlinearity relationship

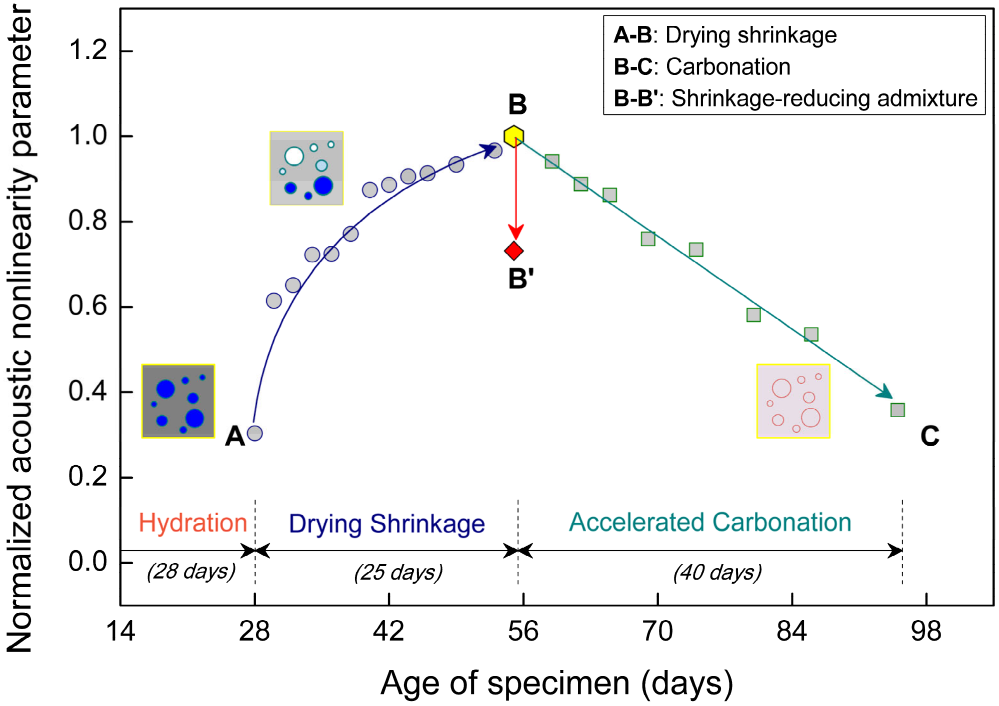


- Increase in wave speed is due to increases in modulus & density
- Decrease in β is due to the $CaCO_3$ filling the pre-existing microcracks.



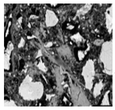
Combination of damage mechanisms

Second harmonic generation of Rayleigh surface waves to track changes in concrete microstructure with the measured acoustic nonlinearity, β



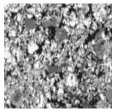
Microstructure changes in hydrated Concrete

- Hydration in fog room (A)
  : Reference
- Drying environment (A→B)
  : 218% increase in *β*



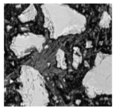
Sant et al. *CCR*, 2011

- Subsequent carbonation (B→C)
  : 64% decrease in *β*



Bertos et al. *JHM*, 2004

- Role of SRA (B→B′)
  : 27% decrease in *β*



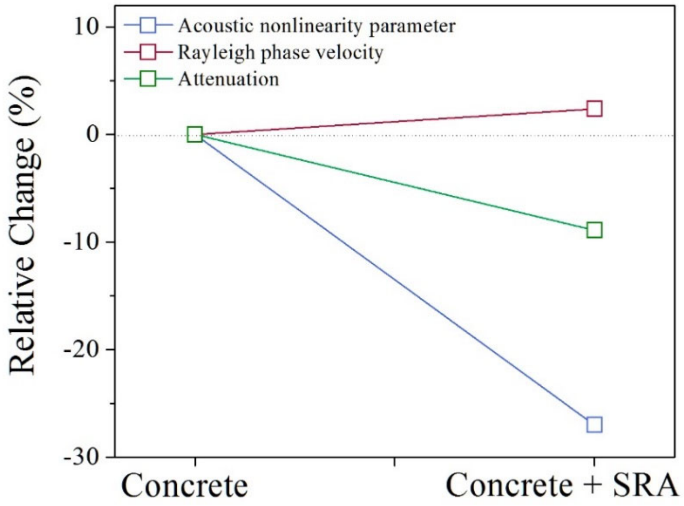
Sant et al. *CCR*, 2011

- Drying shrinkage, and effect of SRA and carbonation is unambiguously distinguished by *β*.
- ***β** plays a crucial role in understanding long-term performance of concrete.*

Kim et al, *Cem Concr Res* (2017)

Nonlinear versus linear ultrasound

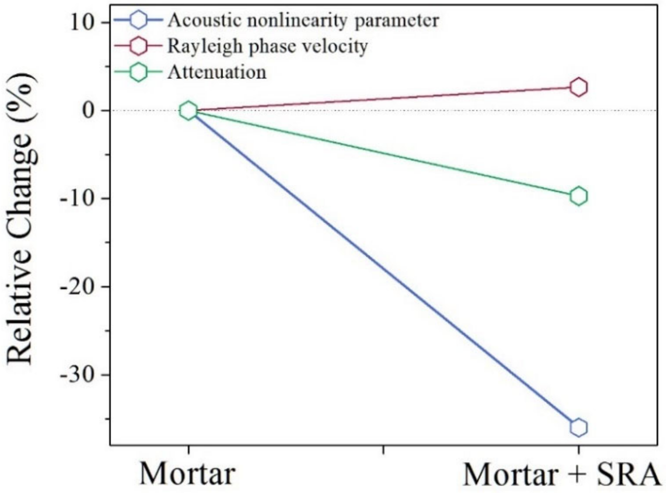
○ Relative change



V_R : 2.4 % ↑

α: 8.9 % ↓

β: 27 % ↓



V_R: 2.7 % ↑

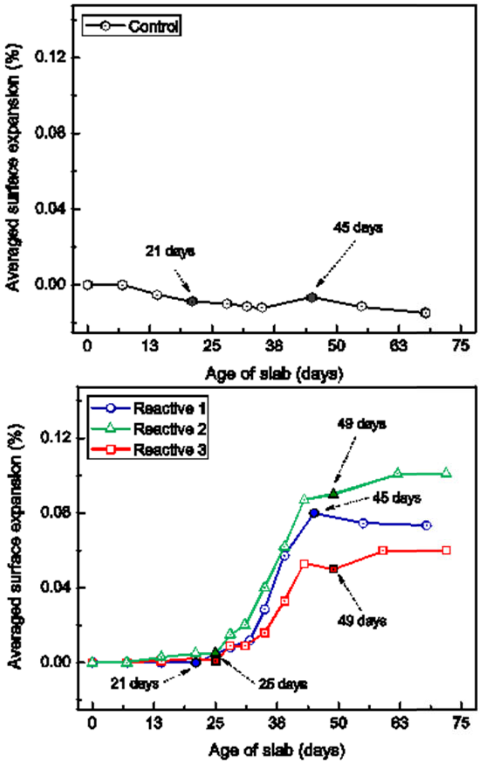
α: 9.7 % ↓

β : 36 % ↓

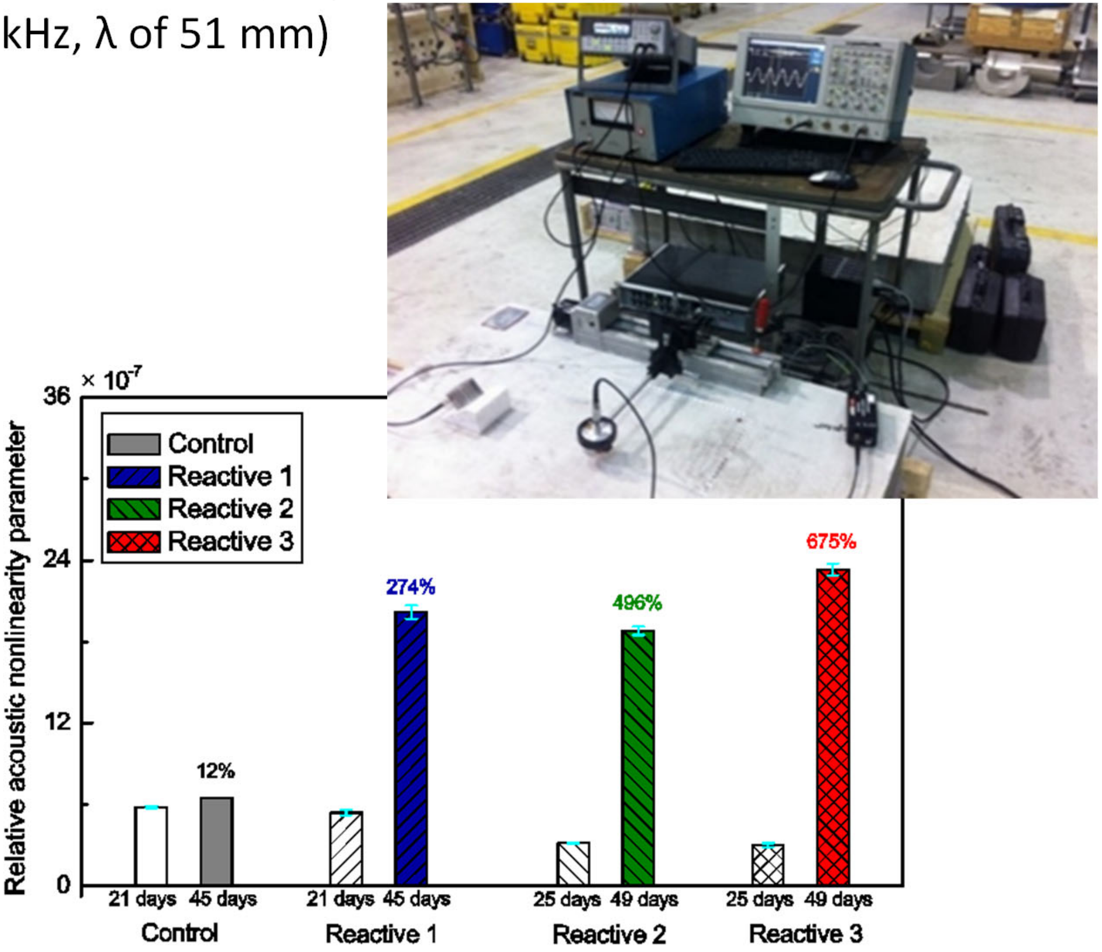
- Summary
  - ***β*** > *attenuation (~3 times) > Rayleigh phase velocity (~12 times)*
  - High sensitivity of *β* reveals causal link b/w drying shrinkage and the effect of SRA.
  - Results show causal links between the effect of SRA and the change in *β.*
  - *The SRA plays a crucial role in reducing drying shrinkage and microcracks*

Tracking ASR in large-scale concrete slabs

- Quantitative characterization of alkali-silica reaction (ASR) ***microscale damage*** in large-scale (1220 x 915 x 200 mm) concrete slabs.
- Second harmonic generation of Rayleigh waves using non-contact air-coupled receiver. (48 kHz, λ of 51 mm)



Independent measure
of global expansion as
a surrogate for ASR damage

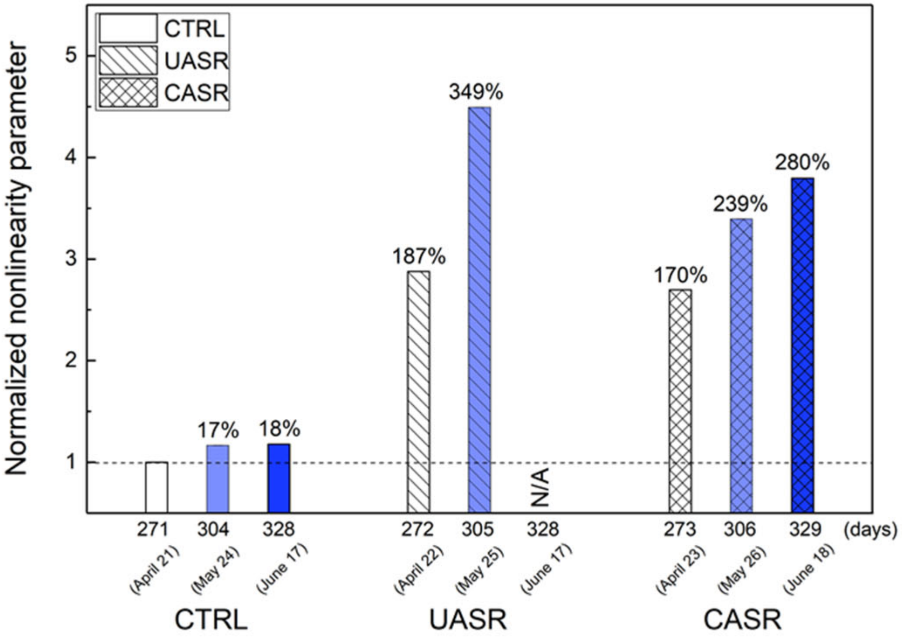


Measured Acoustic Nonlinearity, β

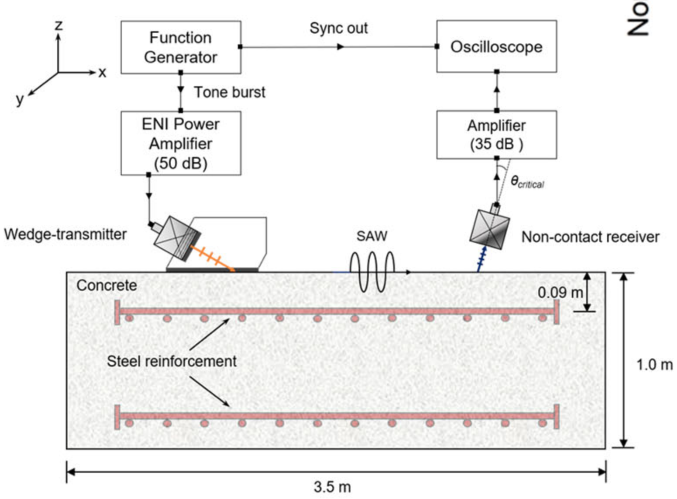
Kim et al, *JNDE* (2017)

Tracking ASR in full-scale NPP mockups

- Three full-scale thick-walled reinforced 3.5 x 3.0 x 1.0 m concrete blocks
- Control, confined and unconfined. Independent measurements of expansions



Measured Acoustic Nonlinearity, β



Diffuse ultrasound

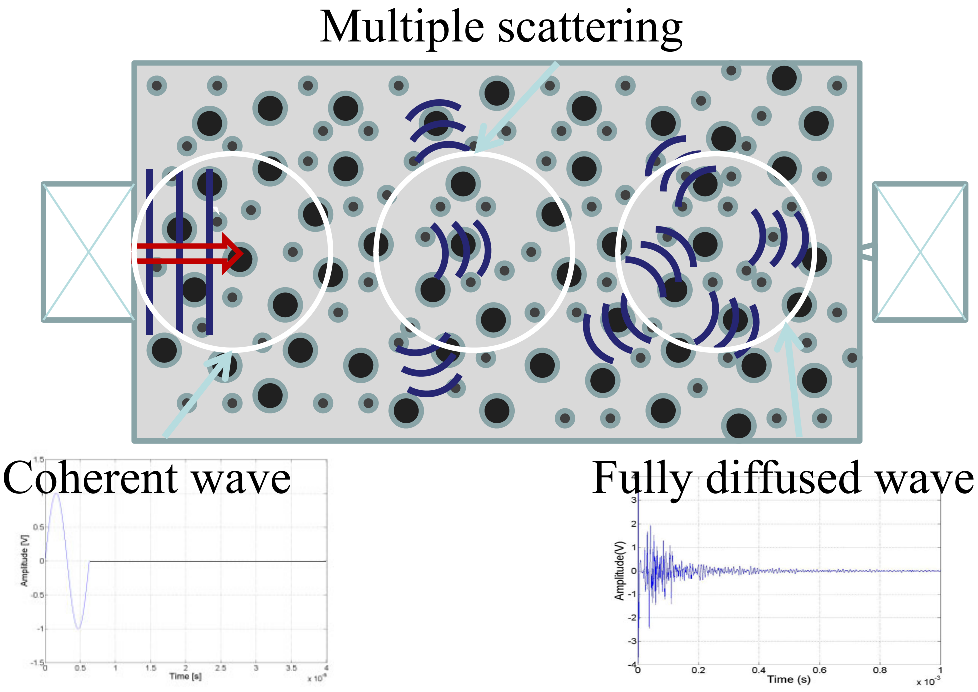
❑ Diffusion approximation

$$D(f)\nabla^2\langle E(x,t,f)\rangle - \frac{\partial}{\partial t}\langle E(x,t,f)\rangle - \sigma(f)\langle E(x,t,f)\rangle = P(x,t,f), \forall x \in \mathrm{B}.$$

where $E(x,t,f)$ is spectral energy density of waves, $P(x,t,f)$ is the spectral source energy density and $\langle\cdot\rangle$ is the expected value operator.

The diffusivity, D(f) [m^2/s] : the diffusion rate of the ultrasonic field

The dissipation, σ(f) [1/s] : the rate of loss of energy



High frequency excitation

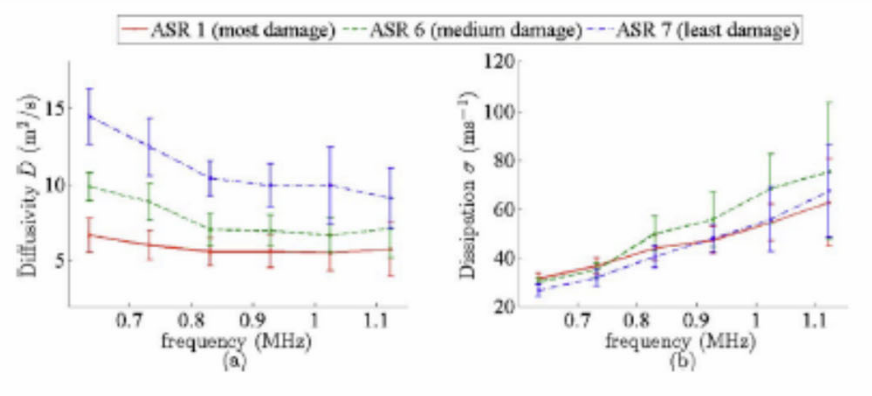
high resolution

The detection of smaller sized defects such as distributed microcracks or shallow cracks (< 8 in)

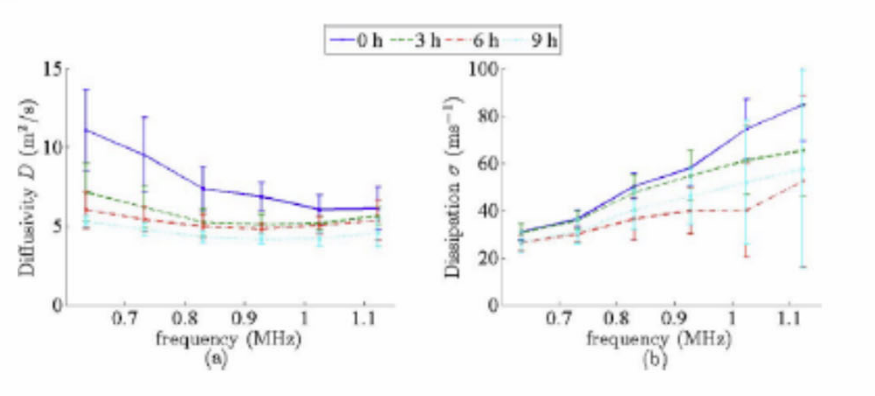
ASR and thermal damage

Damage detection using diffuse ultrasound
Diffusivity and Dissipation

ASR Damage



Thermal Damage

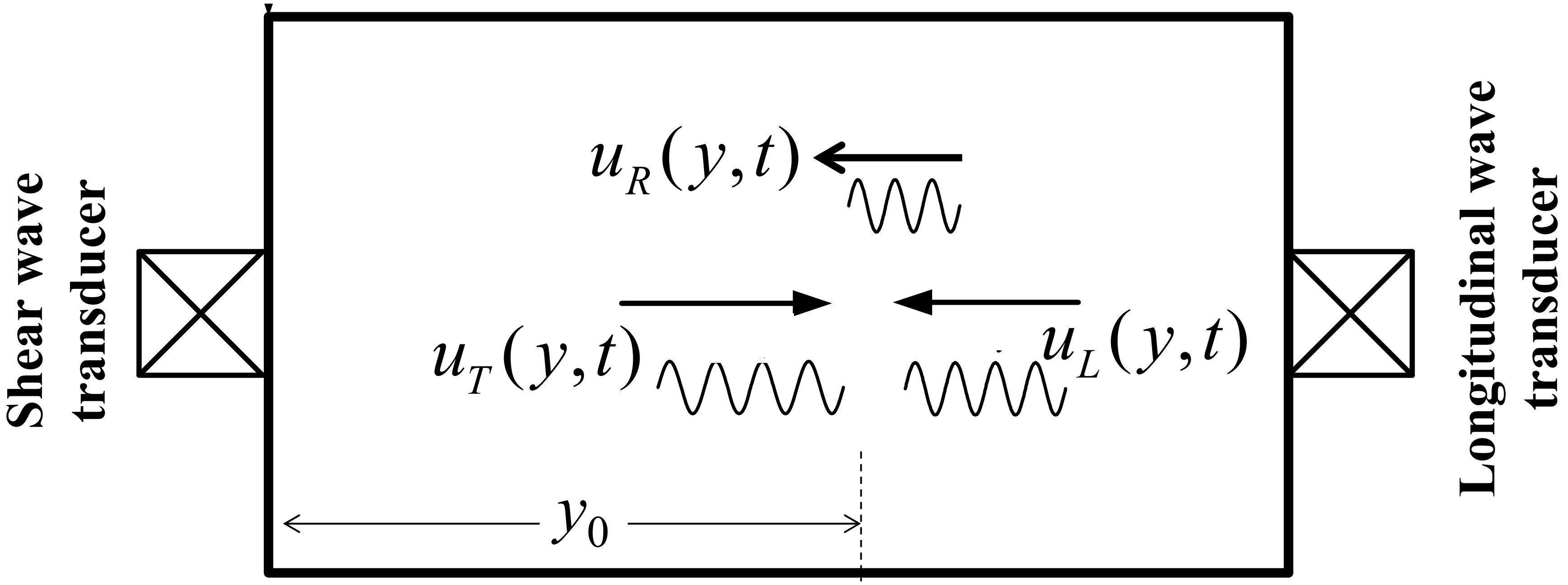


For ASR damage, diffusivity shows a clear trend of decreasing with increasing damage, while dissipations are insensitive.

For thermal damage the increase in microcracking with increasing thermal time is evident in a decrease in diffusivity.

Deroo, Kim, Qu, Sabra, Jacobs JASA (127) 2010

Exploit wave mixing for depth penetration



Resonant Condition ⇒

$$\frac{\omega_L}{\omega_T} = \frac{2c_L}{c_L - c_T}$$

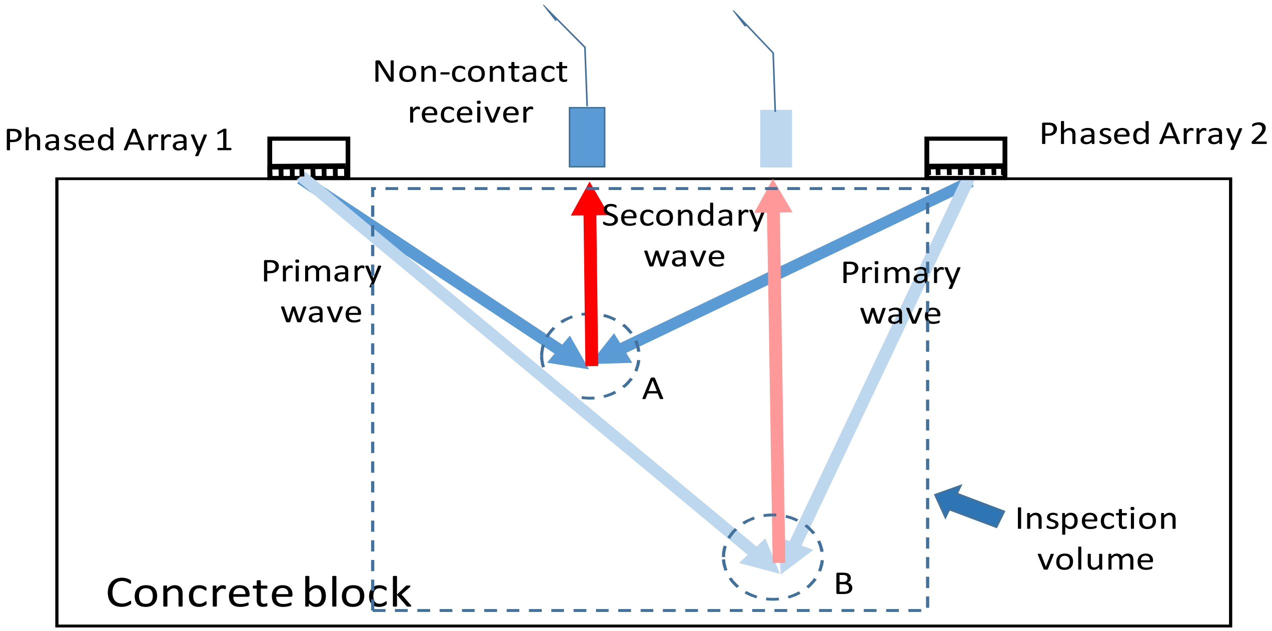
$$A = \frac{\beta_T(y_0)U(y_0)V(y_0)\omega_T^2 l}{2c_T(c_L - c_T)}$$

Resonant Shear Wave ⇒

$$u_R(y,t) = A\cos[\omega_R(t + \frac{y}{c_T})]$$

$$\omega_R = \frac{c_L + c_T}{c_L - c_T}\omega_T$$

Scan using wave mixing and phased array



Possible to scan the specimen nonlinearity by shifting the region of wave interaction

Conclusions

- *Sensitivity:* NLU sensitive to micro and nanoscale scale driven damage and material state
- *Selectivity:* NLU measures single parameter, β that is sensitive to multiple material state features
- Prognostics requires integration of multi-physics measurements and physics-based, materials models

Questions

Thank You. Questions?