# Incorporation of Fibers to Address Problems Related to the Brittleness of Concrete


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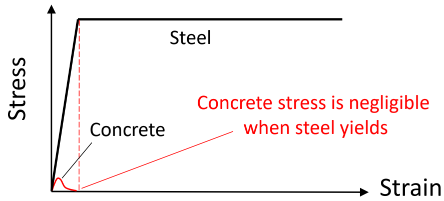
# Outline of the Presentation

- Brittleness of Concrete and Effects of Fiber Incorporation
- Beneficial Applications of Fiber Reinforced Cementitious Materials
  - Repair of concrete members with severely corroded steel rebar
  - Development of Leak-proof basement walls
  - Sprayable material for tunnel lining with very high blast resistance
- Conclusions and Outlook

# Brittleness of Concrete and its Implications

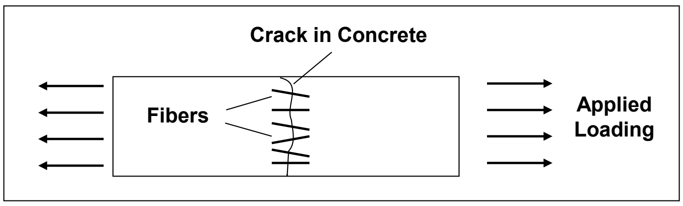
- Concrete is very weak in tension
  - Tensile strength around 3 to 4 MPa
  - Tensile failure occurs at very low tensile strain (<0.02%)
  - Rapid drop in stress after strength is reached
    - → Brittle Behavior
- Implications of brittle behavior
  - In reinforced concrete, the tensile load carrying capacity of concrete cannot be superposed to that of the steel rebar, so it is completely neglected in design
  - Cracks propagate and open easily after they are formed
    - Large amount of steel reinforcements are often required for crack control
  - Low energy absorption capability under cyclic loading, impact or blast

Brittle Failure of Unreinforced Concrete Member

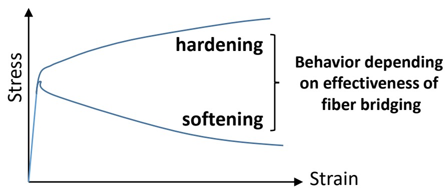



Stress vs Strain Relation of Concrete and Steel

# Improvement of Tensile Behavior by Fiber Addition



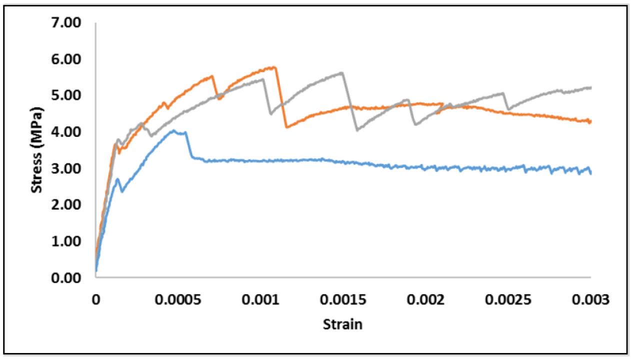

Bridging of a Crack by Fibers




Tensile Stress vs Strain Relation of Fiber Reinforced Concrete

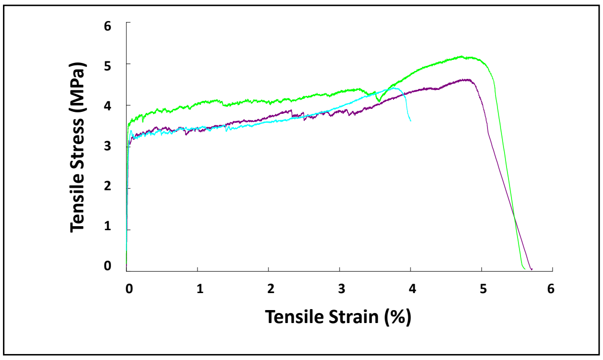
- Fibers provide bridging stress along the crack to control its propagation and opening
- Effectiveness of fiber bridging depends on
  - Volume fraction of fibers
  - Bonding/friction at the fiber/matrix interface
  - Fiber radius (r) and length (L) – maximum bridging force increases with L/r
  - Deformations along the fiber or at the fiber end which can improve anchorage in the matrix
- The post-cracking stress may increase or decrease with crack opening, but can contribute to the tensile load carrying capacity of concrete
- Sliding and pull-out of fibers from the cementitious matrix increase energy absorption significantly
- Properly designed cementitious composites can exhibit very high ductility accompanied by the formation of closely spaced fine cracks
  - Crack control becomes an intrinsic property (NO need to add steel reinforcements for this purpose)

# Examples of Fiber Reinforced Cementitious Composites




**Mortar with 2% of Hooked-end Steel Fiber**

- This is a kind of conventional fiber reinforced mortar with limited hardening behavior but it can carry significant stress after yielding of steel reinforcements




**Mortar with 2% of PVA Fibers**

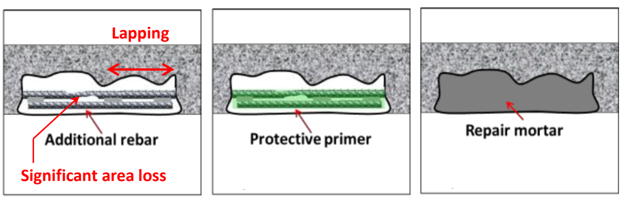
- This composite exhibits hardening behavior up to 4-5%, accompanied by the formation of multiple fine cracks
- Referred to as Engineered Cementitious Composites (ECC) or Strain-hardening Cementitious Composites (SHCC)

# A Novel Fiber Reinforced Repair Mortar for Concrete Beams/Slabs with Severe Steel Corrosion

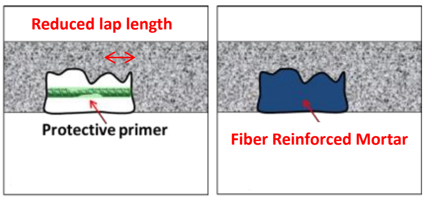
- When steel reinforcing bar is under heavy corrosion (>15% in area loss according to HK practice), lapping of a new piece of rebar is necessary
- To provide sufficient bond length, a significant amount of sound concrete (with an extent equal to 40 times the diameter of new rebar) has to be removed from both sides of the corroded region
  - This will greatly increase the cost and time associated with the repair

New approach (developed by HKUST, Chun Wo Construction Co. and NAMI under ITF support)

- fibers are placed inside the repair mortar to carry tensile load so it is not necessary to add a new rebar
- As the mortar is in direct contact with the rebar, stress transfer should be more effective, so the required bond length can be reduced



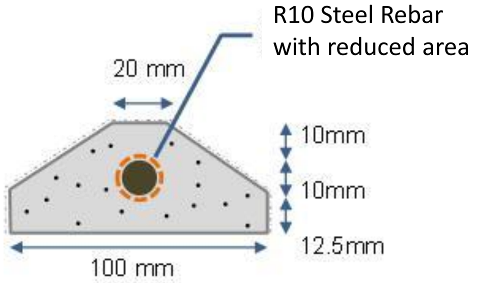

**Conventional repair with additional rebar**




**New approach using fiber mortar**

# Feasibility of the Approach for Old Housing Estates in Hong Kong

- Significant steel area loss (up to about 40%) is common for units in public housing estates with age exceeding 40 years
- There are over 100,000 units reaching such an age so the problem is very significant
- Focus is put on the repair of slabs: 10mm mild steel rebars were normally employed with concrete cover of 12.5mm




**<u>Typical Geometry of Repair Mortar Patch with 'Conservative' Dimensions</u>**
(according to Housing Department)

Cross-sectional Area of Repair Mortar Patch = 2371mm$^2$

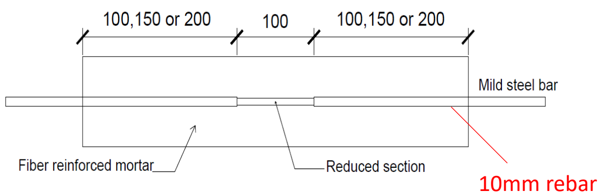
Tensile stress to compensate 40% loss in steel area
= 40% rebar area x rebar strength /mortar area
= $(40\% \times \pi \times 10\text{mm}^2 / 4) \times 250\text{MPa} / 2371\text{mm}^2$
= 3.31MPa

Hence, a fiber reinforced mortar with **tensile strength of 3.5MPa or above** will suffice

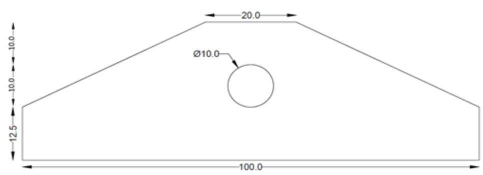
**From experience, this is achievable with the use of hooked-end steel fibers. To prevent rusting, stainless steel fibers is chosen.**

# Testing to Determine the Required Bond Length

- Based on direct tensile tests, the target strength of 3.5 MPa was achievable by adding 2% of hooked end fibers
- Loading needs to be transferred from the full steel section to the section with reduced area due to corrosion
    - The required bond length is an important design parameter
- Testing performed on a specimen with reduced steel rebar area in the middle
- Section of the specimen follows the geometry of a typical patch



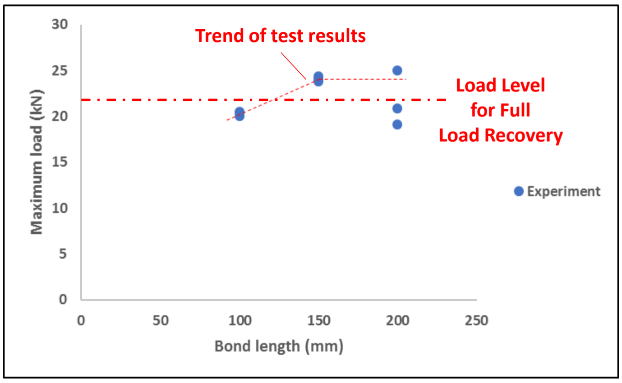

**Bond Test Specimen**




**Section of the Specimen**

# Typical Test Results

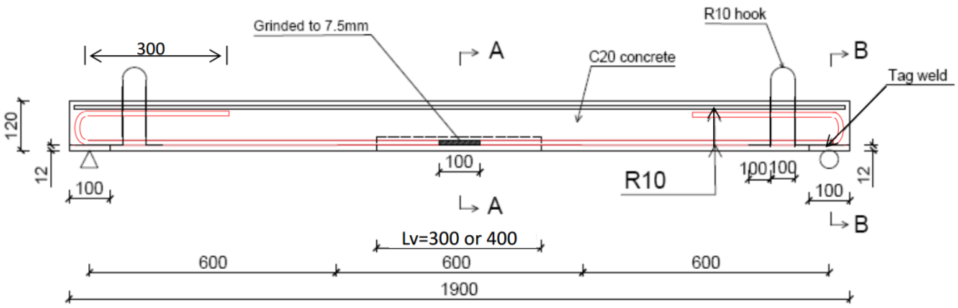
**Maximum Load**
**Vs**
**Bond Length**




- 150mm bond length is sufficient to recover full strength of 250MPa rebar
- With 100mm bond length, over 90% of the load capacity can be recovered
- Further studies on slabs will be performed with 100mm and 150mm bond length

# Specimens for Four-Point Bending Test

- Specimens with single 10mm rebar (middle grinded to 7.5mm) were prepared
- The two ends of the embedded rebar were hooked to avoid bond slip
- The Length of trapezoid void, Lv, were set as 300mm and 400mm to further investigate effect of bond lengths (which are 100mm and 150mm respectively) between repair mortar and steel rebar



# Load Recovery Achieved with the Repair Mortar

- Besides the repaired concrete members, concrete beams with steel rebars of reduced area were also tested, so the contribution of mortar can be deduced
  - Steel used in the test had yield strength much higher than 250MPa; after finding the mortar contribution, it is used to calculate the % recovery for 250MPa steel rebar
- With a new mortar developed specifically for this application, load recovery was over 130% for 100mm bond length and over 140% for 150mm bond length
  - Full recovery can be achieved even with 100mm bond length

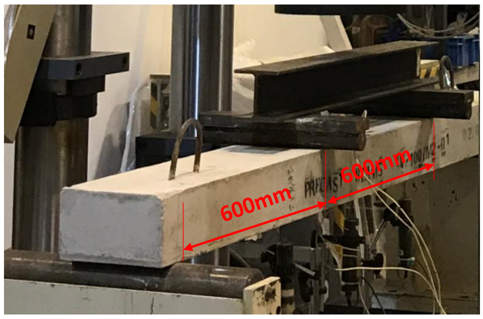
**Sample Preparation**

Surface roughening

The reinforced mortar strips

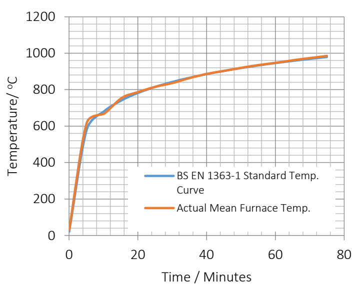
Performing the patching

**Testing of Beam Member**

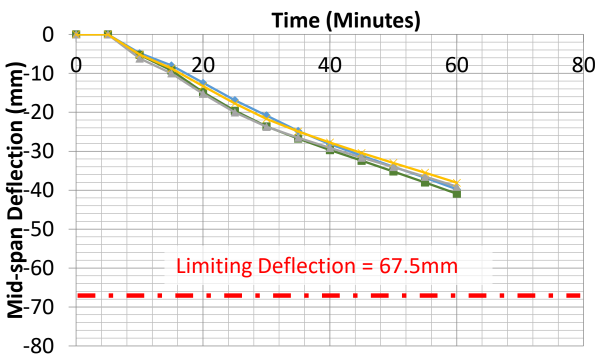



# Full-scale Fire Test of Repaired Concrete Slabs

- Four specimens prepared for fire testing, one control and three with a steel rebar exhibiting 40% area reduction, repaired using fiber reinforced mortar
- For the repair, the bond length on each side was 150mm
- Following code requirements, specimens were loaded with uniform dead weight equivalent to 5kPa during fire exposure
- The deflection and deflection rate are both within limits specified in the fire standard




Temperature vs time curve according to BS EN 1363-1



# Benefits of the New Repair Method

- Time and cost savings
  - For a typical area with corrosion over 100mm of the rebar, the time and cost savings are shown in the following table
- In addition, there are other benefits
  - Reduced construction waste and less dust: 60% less concrete hacking
  - Less noise: 40% shorter concrete hacking time
  - Less time of working-at-height: enhanced safety for workers

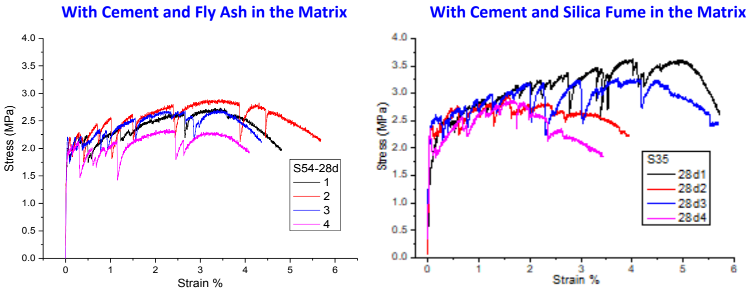
| Items | Conventional Method | New Approach |
| --- | --- | --- |
| length of concrete to be removed | 1.0 | 0.44 |
| plant and material costs | 1.0 | 0.89 |
| labour cost | 1.0 | 0.83 |
| **repair time** | 1.0 | **0.60** |
| **total equivalent cost** | 1.0 | **0.85** |

# ECC for Leak-Proof Basement

- Water Leakage is a big problem with basements
- Current Approach
  - Provide additional steel reinforcements (over that required for ultimate limit state) to control crack openings
  - Increase thickness of the wall to reduce tensile stress acting on the steel reinforcement, so crack opening is smaller
- An innovative approach
  - Use Engineered Cementitious Composites (ECC) with intrinsic crack control ability (e.g., crack opening less than 0.1mm at serviceability limit state)
  - Crack control at serviceability state is then automatically satisfied

# Cost-Effective ECC Developed in Hong Kong

- Collaboration among NAMI, Hip Hing Construction Company Limited and HKUST in an ITF project has developed a low cost PET fiber suitable for ECC via a novel surface treatment technology
  - Recycled PET fiber can be used
  - Fiber cost < 30% of commonly used PVA and PE fibers
- SHCC with compressive strength > 50MPa and tensile strain capacity over 3% has been successfully prepared
- Very low crack opening up to 0.25% strain




Tensile stress-strain Curves

| | ECC with Fly Ash | ECC with silica fume |
|---|---|---|
| Treated PET Fibers | 40micron, 12mm, 2.5% | |
| 28d comp strength (MPa) | 59.3±1.85 | 67.47±2.04 |
| 28d tensile strength (MPa) | 2.55±0.19 | 2.93±0.57 |
| 28d tensile strain (%) | 3.77 | 3.75 |
| 28d max crack width (mm) measured at 0.25% strain | 0.076 | 0.085 |

# Basement Wall Constructed with ECC

- Based on experimental results, compressive strength of ECC is taken to be 45MPa
- At Ultimate limit state (ULS), tensile capacity of ECC is completely ignored for conservative design
  - No safety issue even if polymeric fiber is burnt in a fire
- At Serviceability limit state (SLS), tensile capacity of ECC is used for crack width control only
  - Based on test results, crack width is less than 100 micron for tensile strain up to 0.25%
  - Crack width of 0.2mm is allowable in conventional RC design
  - With ECC, we conservatively limit the surface tensile strain to 0.2% so the crack width will not exceed 0.1mm
- To illustrate the advantages of using ECC, several examples are taken form a real basement design
  - In all cases, design is governed by crack control at SLS
  - The steel area at ULS was found to be over-designed in some cases
    - These values are used as reference for the designs with ECC

      (Note: steel content affects bending stiffness and hence surface tensile strain)
  - Deflection checking also carried out at SLS when steel area or wall thickness is reduced

# Saving of Steel Reinforcement with ECC

## Conventional RC Design

## Design with ECC

| Cases | R/C | | Tensile strain at surface | Estimated crack width | R/ECC | Tensile strain at surface | # Estimated crack width |
|---|---|---|---|---|---|---|---|
| | Provision of Reinforcement in ULS | Provision of Reinforcement in SLS | | | Provision of Reinforcement in ULS & SLS | | |
| (1). BW8-700 THK | 8378 mm$^2$ | 16755 mm$^2$ | 0.08% | 0.189 mm | 8378 mm$^2$ | 0.11% | $\leq$ 0.1 mm (0.2% strain) |
| (2). BW21-700 THK | 5362 mm$^2$ | 10723 mm$^2$ | 0.04% | 0.098 mm | 5362 mm$^2$ | 0.04% | $\leq$ 0.1 mm (0.2% strain) |
| (3). 800-THK | 3200 mm$^2$ | 8042 mm$^2$ | 0.07% | 0.077 mm | 3200 mm$^2$ | 0.08% | $\leq$ 0.1 mm (0.2% strain) |

Over-designed in these cases

| Cases | Reinforcement Saving by R/ECC |
|---|---|
| (1). BW8-700 THK | $\frac{16755-8378}{16755}x100 = 50\%$ |
| (2). BW21- 700 THK | $\frac{10723-5362}{10723}x100 = 50\%$ |
| (3). 800-THK | $\frac{8042-3200}{8042}x100 = 60.2\%$ |

≥50 % saving in reinforcement

# Reduction of Wall Section with ECC

- In addition to saving steel, it is also possible to reduce the wall section to increase usable space
- As crack width in ECC stays small up to 0.2% strain, higher strain is allowed at the wall surface so wall thickness can be reduced

## Conventional RC Design

## Design with ECC (allowing higher tensile strain)

| Cases_R/C | R/C | | Tensile strain at surface | Estimated crack width | Cases_R/ECC | R/ECC | Tensile strain at surface | # Estimated crack width |
|---|---|---|---|---|---|---|---|---|
| | Provision of Reinforcement in ULS | Provision of Reinforcement in SLS | | | | Provision of Reinforcement in ULS & SLS | | |
| (1). BW8-700 THK | 8378 mm$^2$ | 16755 mm$^2$ | 0.08% | 0.189 mm | (1). BW8-600 THK | 8378 mm$^2$ | 0.16% | ≤0.1mm (0.2% strain) |
| (2). BW21-700 THK | 5362 mm$^2$ | 10723 mm$^2$ | 0.04% | 0.098 mm | (2). BW21-425 THK | 5362 mm$^2$ | 0.17% | ≤0.1mm (0.2% strain) |
| (3). BW-800-THK | 3200 mm$^2$ | 8042 mm$^2$ | 0.07% | 0.077 mm | (3). BW-500-THK | 8042 mm$^2$ | 0.13% | ≤0.1mm (0.2% strain) |

Over-designed in these cases

Smaller crack width than RC

| Cases | Final provision of reinforcement by R/C | Final provision of reinforcement by R/ECC | Final provision of reinforcement reduction by R/ECC | Thickness by R/C | Thickness by R/ECC | Section thickness reduction by R/ECC |
|---|---|---|---|---|---|---|
| (1). BW8 | 16755 mm$^2$ | 8378 mm$^2$ | $\frac{16755-8378}{16755}x100 = 50\%$ | 700 mm | 600 mm | $\frac{700-600}{700}x100 = 14\%$ |
| (2). BW21 | 10723 mm$^2$ | 5362 mm$^2$ | $\frac{10723-5362}{10723}x100 = 50\%$ | 700 mm | 425 mm | $\frac{700-425}{700}x100 = 39\%$ |
| (3). BW | 8042 mm$^2$ | 8042 mm$^2$ | $\frac{8042-8042}{8042}x100 = 0\%$ | 800 mm | 500 mm | $\frac{800-500}{800}x100 = 37.5\%$ |

14 to 39% reduction in thickness

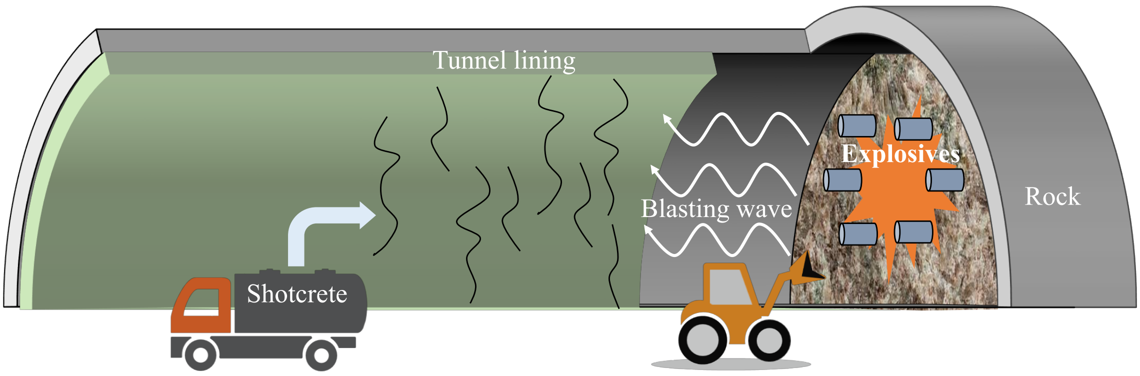
# Feasibility of ECC for Drill-and-Blast Tunnel Lining

**Current Practice**

- Temporary lining constructed on exposed rock is taken to be damaged during subsequent blasts
- A permanent lining of full thickness will be constructed later
    - Low productivity process and extra rock removal to accommodate the temporary lining

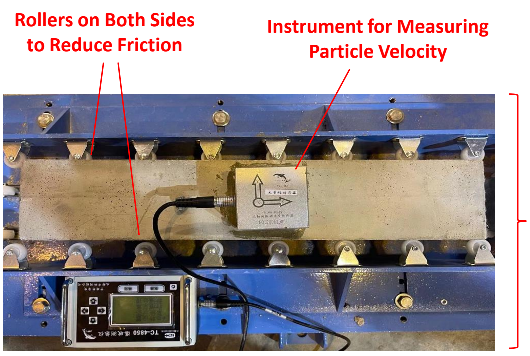
**Plausible Improvement**

- If the lining is made of a material with higher impact resistance such as ECC, it may be possible to construct the permanent lining right after blasting
- Moreover, the time between subsequent blasts can be shortened

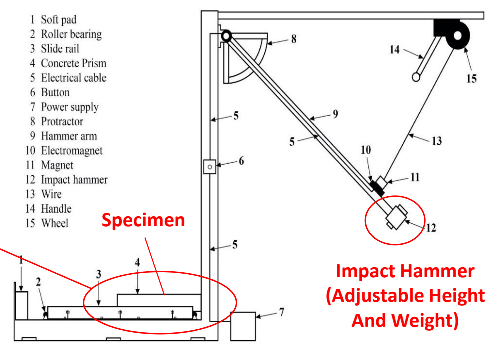



# Research Approach

- A study supported by GEO was conducted together with Prof. Victor Li (University of Michigan)
- Approach followed *GEO Report 102 – A Study on the Effects of Blasting Vibration on Green Concrete*, developed by Prof. Peter Lee, Prof. Albert Kwan and Dr. Herbert Zheng in 1998
- Blast resistance is defined in terms of the Peak Particle Velocity (PPV) of the material during vibration that would lead to tensile strength reduction of <30%
- In the laboratory, vibration is induced by impact loading rather than explosion




Prismatic Specimen before Testing




Testing Set-up

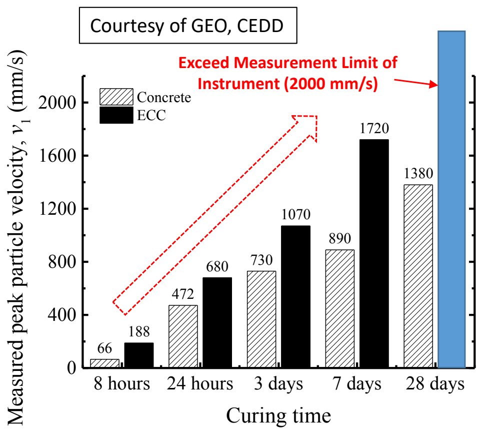
# Experimental Program

- Concrete and ECC specimens were cured for different periods of time before testing
  - 8 hours, 24 hours, 3 days, 7 days and 28 days
- Preliminary impact tests were conducted to find the suitable ranges of hammer height and weight
- To monitor damage in specimens, resonant frequency (RF) test is performed to complement visual inspection
  - Resonance frequency reflects wave velocity in material which decreases with damage
  - Particularly useful for ECC with fine cracks that are hard to identify
- After impact, specimens were cured to 28-day age and then tested under direct tension
- Following GEO Report 102, the allowable PPV is the value leading to 30% reduction in tensile strength of the material

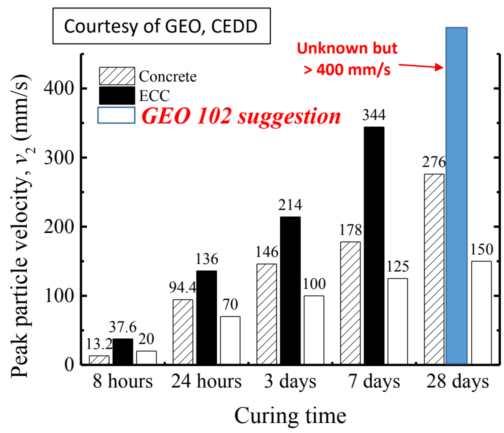

Measurement of Resonance Frequency
for Specimen after Impact

Direct Tensile Test
on Specimen
after Impact

# Test Results and Further Studies




Safe factor = 5
(GEO 102)




- With the use of ECC, the allowable PPV is higher for all curing ages
  - Potential for construction of blast resistant permanent lining
- Further work needs to be performed to
  - study the effect of waveforms representative of blasts
  - determine an allowable PPV more consistent with design practice
  - study the effect of in-situ curing conditions
  - determine other relevant properties of ECC through bond test, EFNARC plate test, etc.

# Conclusions and Outlook

- Brittleness of concrete is a hurdle to the development of more cost-effective designs
- Incorporation of fiber reinforcements can alleviate brittleness by providing residual tensile stress in cracks that can enhance load carrying capacity, control crack width and increase energy absorption
- Fiber reinforced cementitious composites (FRCC) has shown promise for
  - repair of reinforced concrete members with severe steel corrosion
  - crack control in basements to prevent water leakage
  - construction of blast resistant tunnel lining
- Wider application will be facilitated by
  - Better understanding of the behavior of FRCC
  - Field trials to understand issues related to scale-up production, quality control, compliance testing, etc.
  - **Innovative ideas**