Concrete with Alkali-Activated Slag and Nano-Impregnated Carbon fibre Mesh

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This presentation try to address

- What is **alkali-activated slag** (AAS) concrete? Which factors affect the strength and shrinkage of AAS concrete?
- What is the general durability of AAS concrete? How is the acid resistance and temperature stability of the concrete affected when using AAS?
- What potential structures can AAS concrete be suitable for?
- What are the obstacles to the application of AAS concrete in ordinary structures?
- How to improve adhesion between **carbon fiber mesh** and concrete?

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Background

- What is **alkali-activated slag** (AAS) concrete?

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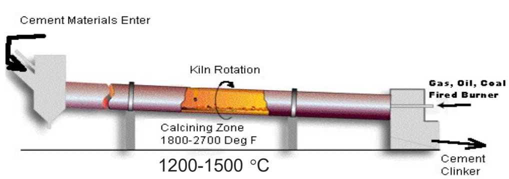
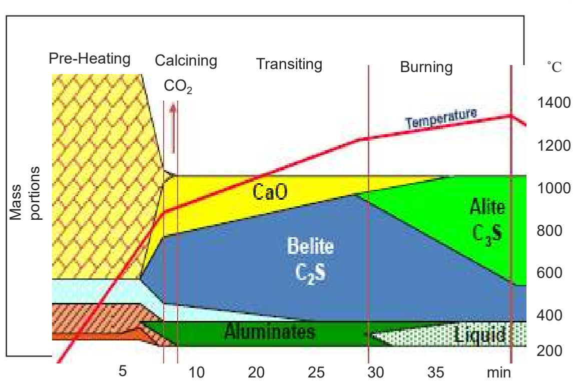
Problem in Portland Cement Production





Calcining process

$CaCO_3 \rightarrow CaO + CO_2$

Molecular weight 56 44

+ CO_2 release from fuel

≈ 0.9 kg CO_2 per kg cement

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History of Alkali-Activated Materials (AAM)

Year	Researcher	Country	Main work
1930	Kuhl	Germany	**Setting** of slags + caustic potash
1937	Chassevent	unknown	**Reactivity** of slags + caustic potash and soda solution
1940	Purdon	Belgium	**Clinker-free cement**: slag + caustic soda or alkalis produced by a base and an alkaline salt
1957	Glukhovsky	USSR	**Soil cement**: hydrous or anhydrous aluminosilicates (glassy rocks, clays metallurgical slags, etc.) + alkalis, proposed cementing system M_2O-MeO-Me_2O_3-SiO_2-H_2O
1982	Davidovites	France	**Geopolymer**: alkalis + a burnt mixture of kaolinite, limestone and dolomite
1990	Tomas Kutti	Sweden	**Alkali Activated Slag Mortar** – Mechanical strengths, shrinkage and structure, Chalmers PhD thesis P-90:6

(M: alkali metal; Me: alkaline earth metal)

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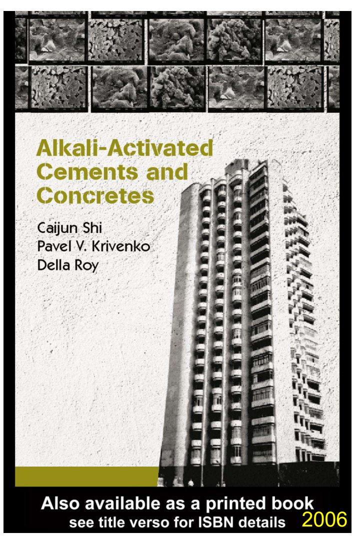
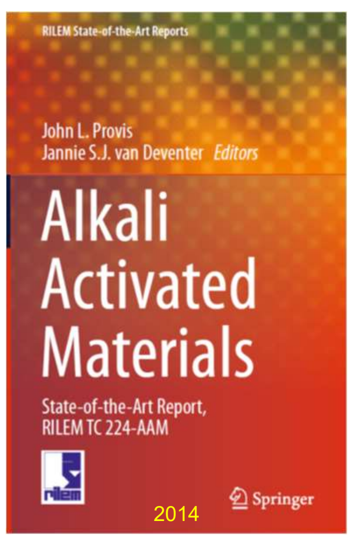
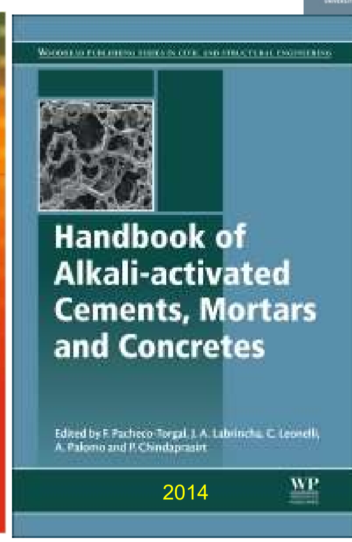
A Hot Topic since 2000







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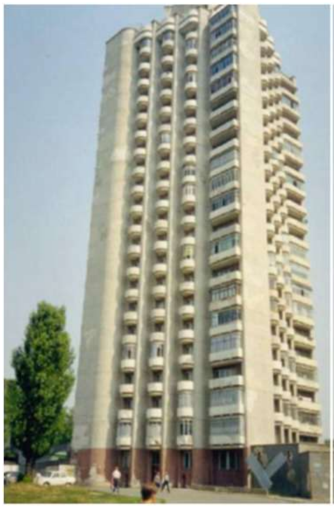
Some Example Buildings Made of AAM



A 24-storey buildig built with AAS on Berezinsa street 2, City of Lipetsk, Russia

Residential building in Mariupol, Ukraine, constructed from AAS precast blocks (exterior clad in plaster)

6-storey office and retail building built with AAS in Anyang City, Henan Province, China

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Groups of Alkali-activator

1. Caustic alkali: MOH (e.g. NaOH, KOH)
2. Non-silicate weak acid salts: M_2CO_3, M_2SO_3, M_2PO_4, MF, etc. (e.g. Na_2CO_3, K_2CO_3)
3. Silicates: $M_2O \cdot nSiO_2$ (e.g. $Na_2O \cdot nSiO_2$, $K_2O \cdot nSiO_2$)
4. Aluminates: $M_2O \cdot n\,Al_2O_3$
5. Aluminosilicates: $M_2O \cdot Al_2O_3 \cdot (2\text{-}6)\,SiO_2$
6. Non-silicate strong acid salts: M_2SO_4 (e.g. Na_2SO_4)

(Glukhovsky et al., 1980)

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Two Big Problems in AAS

- Low CaO/SiO_2 (only about 1) resulting in high shrinkage
- Variable setting time (sometimes it is advantage but sometimes it is too quick to complete casting)

Vinnova research project

Green Cement Based on Ground Granulated Blast furnace Slag (GGBS) (2018 – 2021)

Aim of the project:
Develop fiber reinforced sustainable, competitive and advanced cementitious materials for industrial applications ranging from construction to transportation

Mainly based on alkali-activated GGBS (AAS)

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Important Parameters in Proportioning AAS Concrete

(Which factors affect the strength and shrinkage of AAS concrete?)

- Alkali content (Na_2O by wt% of slag)
- Silica content (SiO_2 by wt% of slag)
- Gypsum content ($CaSO_4 \cdot 2H_2O$ by wt% of slag)

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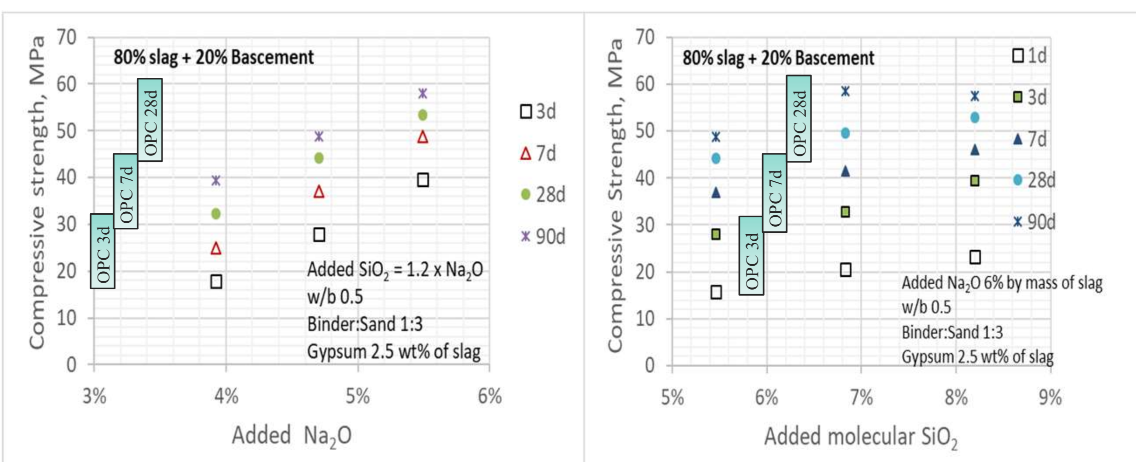
Results from Compressive Strength Test

Alkali-activated slag with different additions of alkali and silica



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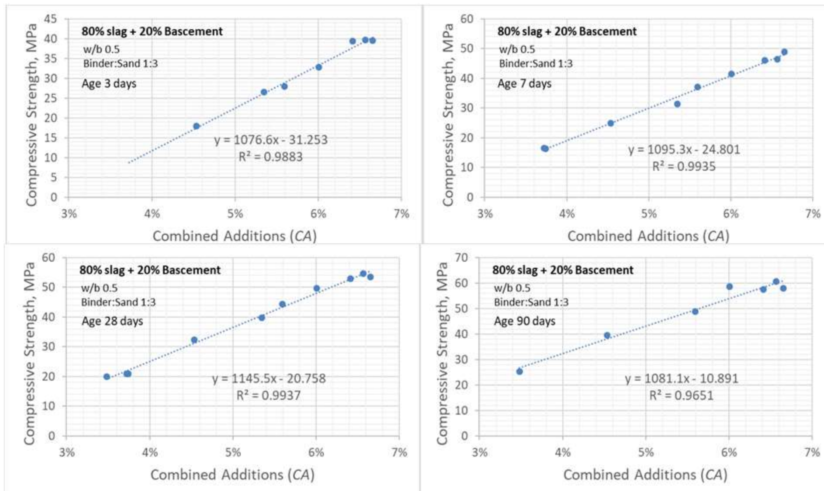
Effect of Combined Additions



CA = Na_2O% + 0.3SiO_2% - 0.3Gypsum%

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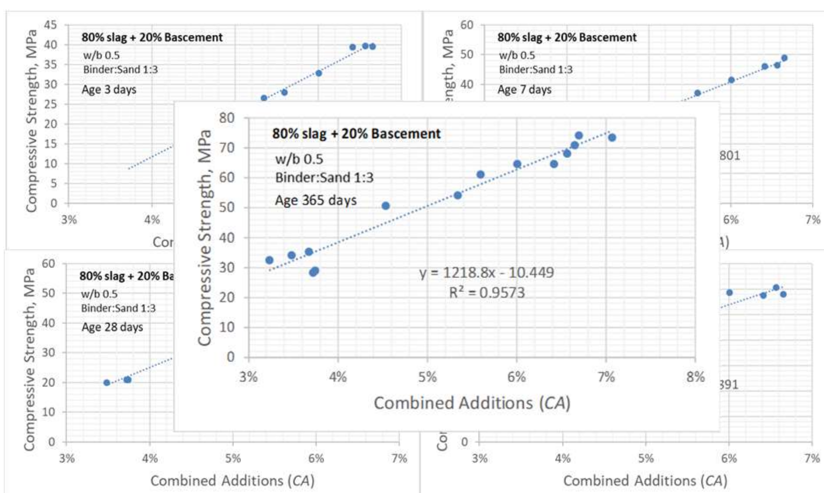
Effect of Combined Additions



CA = Na_2O% + 0.3SiO_2% - 0.3Gypsum%

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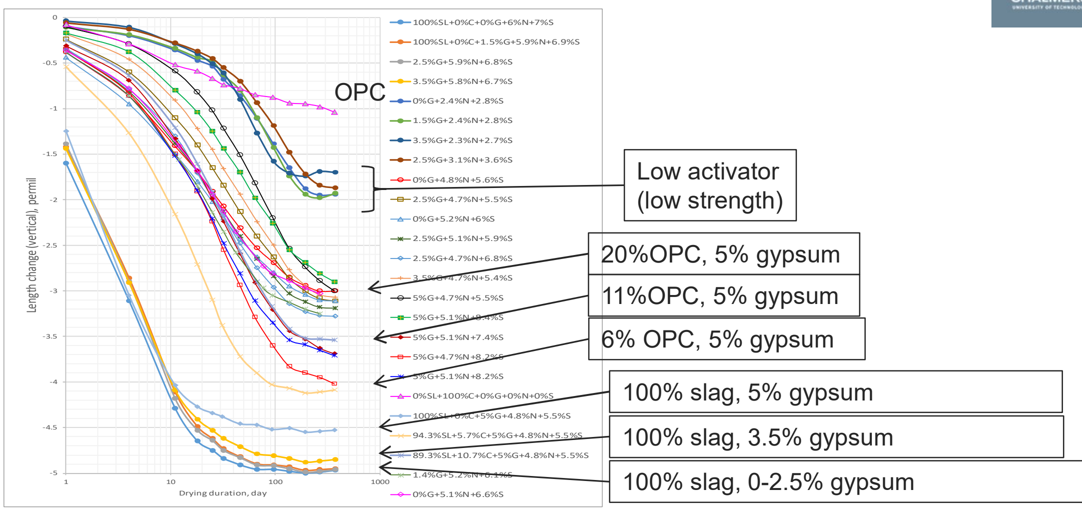
Results from Shrinkage Test



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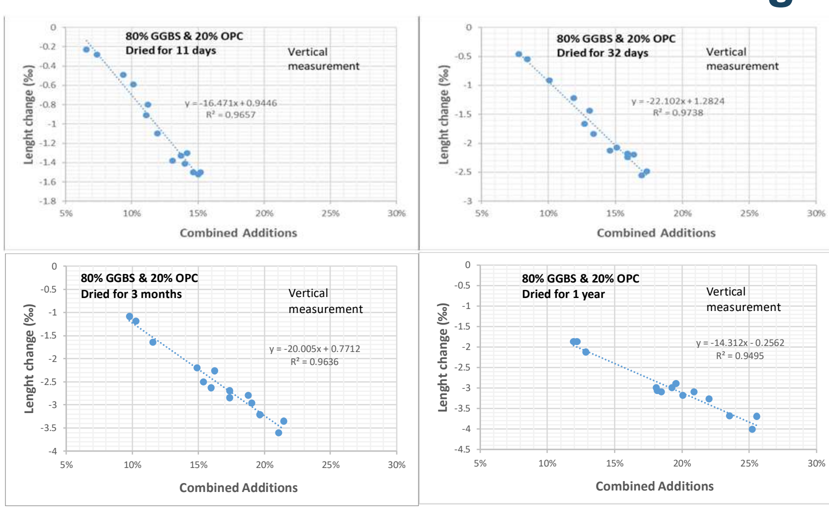
Effect of Combined Additions for Shrinkage



$$CA = Na_2O\% + \alpha \cdot SiO_2\% + \beta \cdot Gypsum\%$$

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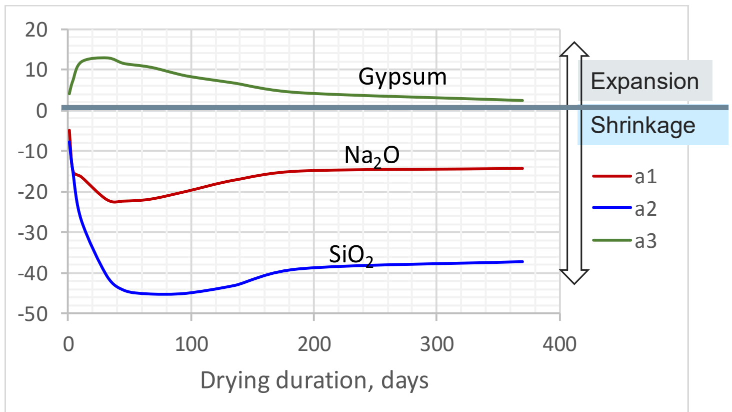
Effect of Combined Additions for Shrinkage

Shrinkage (‰) = $a_1 \cdot Na_2O\% + a_2 \cdot SiO_2\% + a_3 \cdot Gypsum\% + b$



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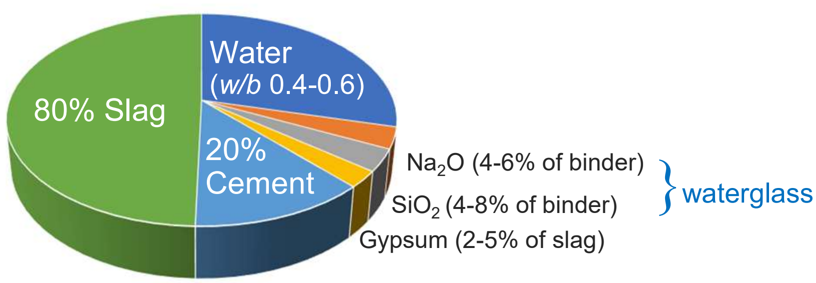
Exemple of Alkali-Activated Binder



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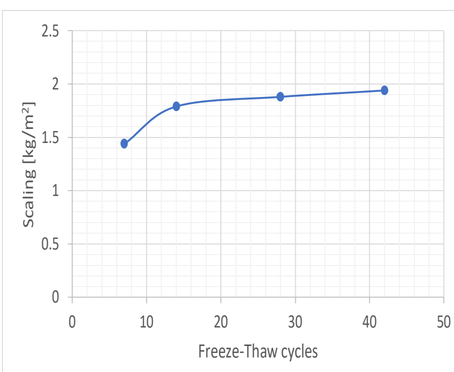
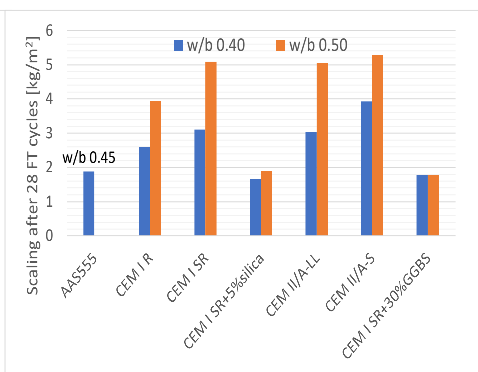
Durability of AAS Concrete

(What is the general durability of AAS concrete? How is the acid resistance and temperature stability of the concrete affected when using AAS?)

- General durability (frost attack, chloride ingress, carbonation)
- Acid resistance
- High temperature stability

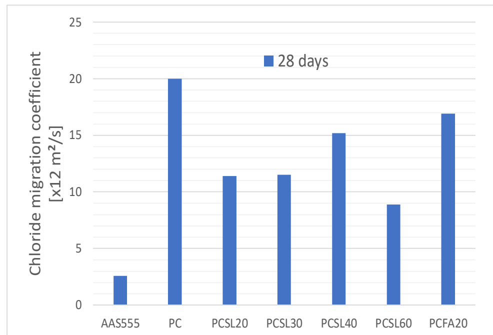
Resistance to Frost Scaling





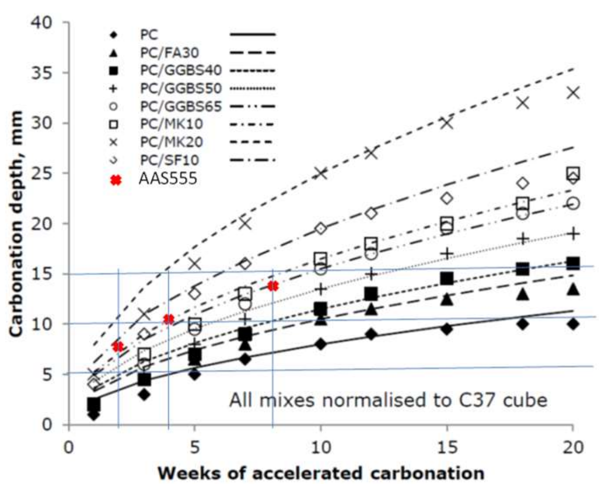
- Similar level of concretes with 5% silica and 30% GGBS,
- Better than those with commercial cement CEM I and CEM II/A.

Resistance to Chloride Ingress



- Significantly better than that of concrete with Portland cement, even blended with GGBS.

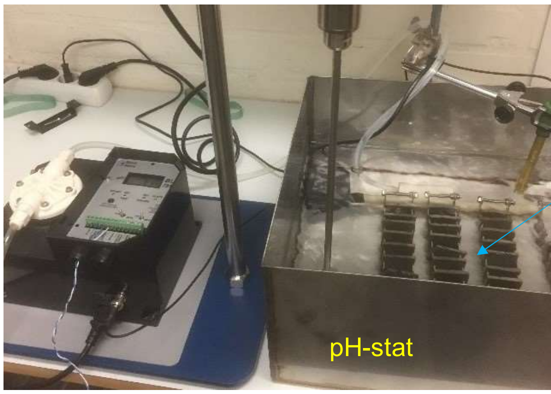
Resistance to Carbonation



- Higher than the plain Portland cement
- Similar as those blended with mineral additions (due to the lack of portlandite as a buffer for carbonation)

Tested under the accelerated and relatively dry condition!

Acid Resistance



Samples

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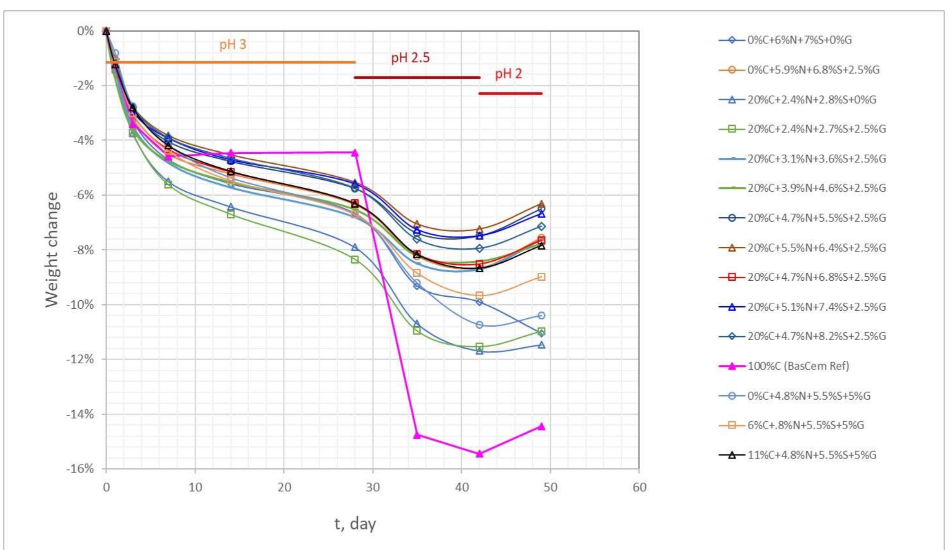
Acid Resistance of AAS Mortar



Sample Ref

Alkali-activated sample

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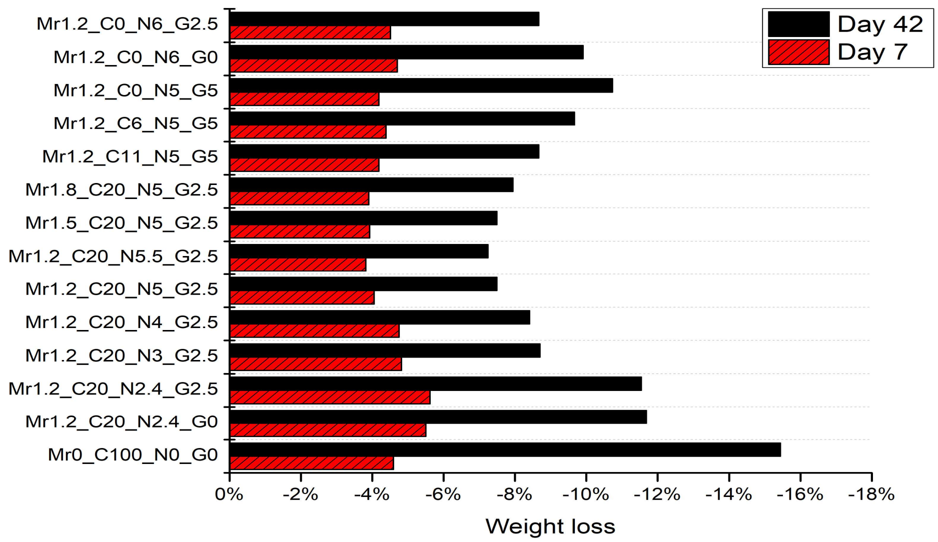
Acid Resistance of AAS Mortar



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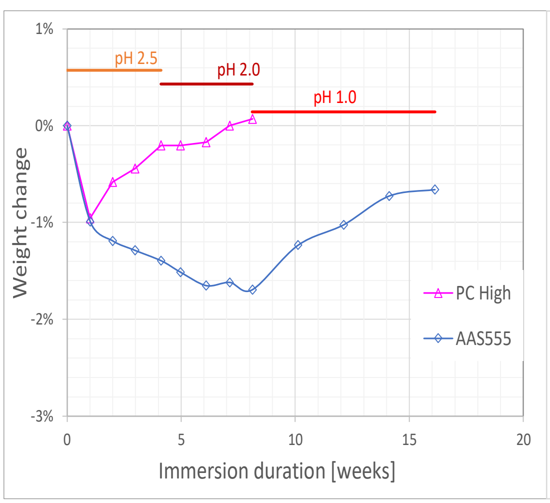
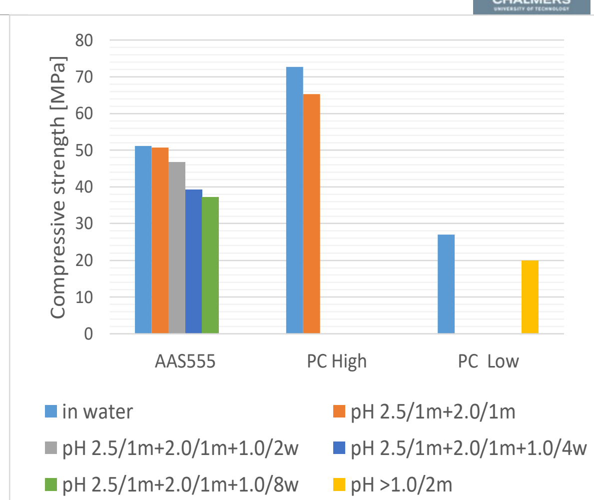
Acid Resistance of AAS Concrete





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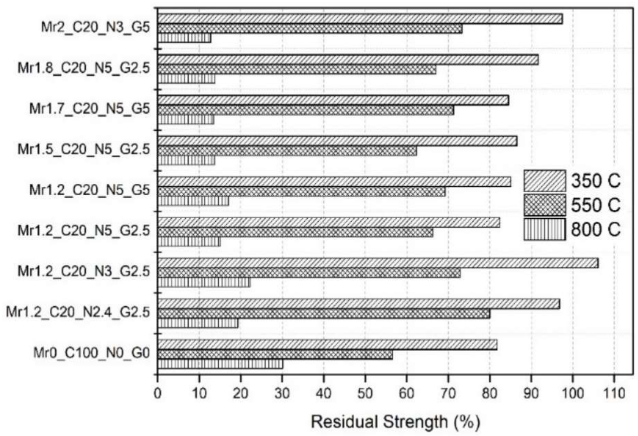
High Temperature Stability of AAS Mortar



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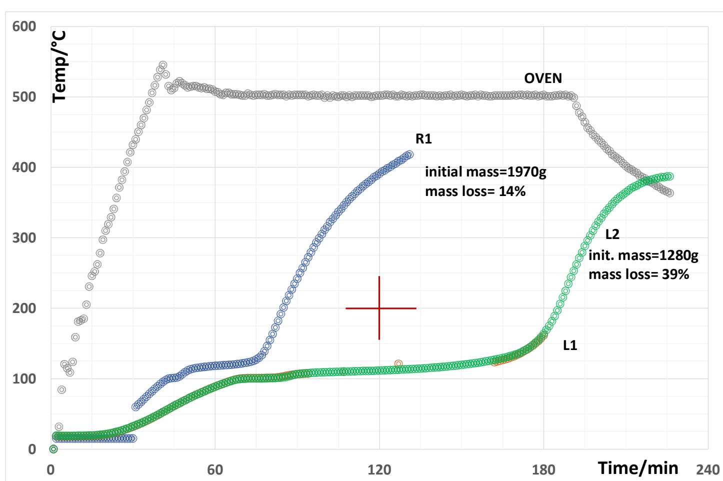
High Temperature Stability of AAS Concrete



R = AAS concrete
L = AAS lightweight concrete (with vermiculite)

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Potential Applications

(What potential structures can AAS concrete be suitable for?)

- Sewage pipes, blocks and elements for infrastructures of wastewater purification;

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Potential Applications

(What potential structures can AAS concrete be suitable for?)

- Composite concrete beams or walls for potential use in modular fireproof safes and vaults

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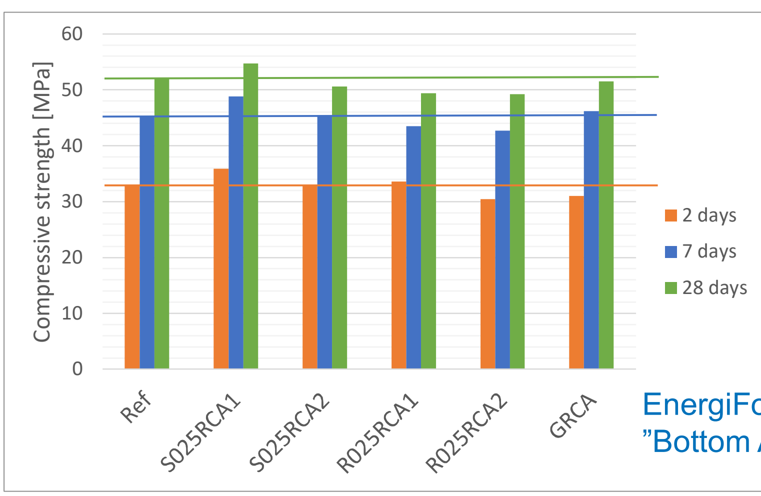
Potential Applications

(What potential structures can AAS concrete be suitable for?)

- Improved aggregate from recycled concrete or waste mineral tailings.

Mortar with Fine Recycled Concrete Aggregate and Bottom Ash



EnergiForsk project 2019-118
”Bottom Ash for Green Aggregate”

Obstacles to Application of AAS

(What are the obstacles to the application of AAS concrete in ordinary structures?)

Technical obstacles:

- Relatively larger drying shrinkage (about 3 times as much as OPC concrete);
- Relatively poor resistance to carbonation (similar to the other SCMs);
- Uncertain air-entraining for resistance to frost scaling; and
- Uncertain superplasticizers for adjusting workability of fresh concrete

Non-technical obstacles:

- **National regulations or standardization!!!**

USSR Industry standard OST 67-11-84: "Slag Alkaline Binders. Technical Specifi cations" (1984)
Ukrainian Technical Specifications TU 10.20 UkrSSR 169-91: "A slag alkaline binder on sulfate-containing compounds of alkali metals" (1991)
BSI PAS 8820: "Construction Materials -Alkali Activated Cementitious Materials – Specification" (2016)
Chinese standard JGJ/T439 "Technical standard for application of alkali-activated slag concrete" (2018)

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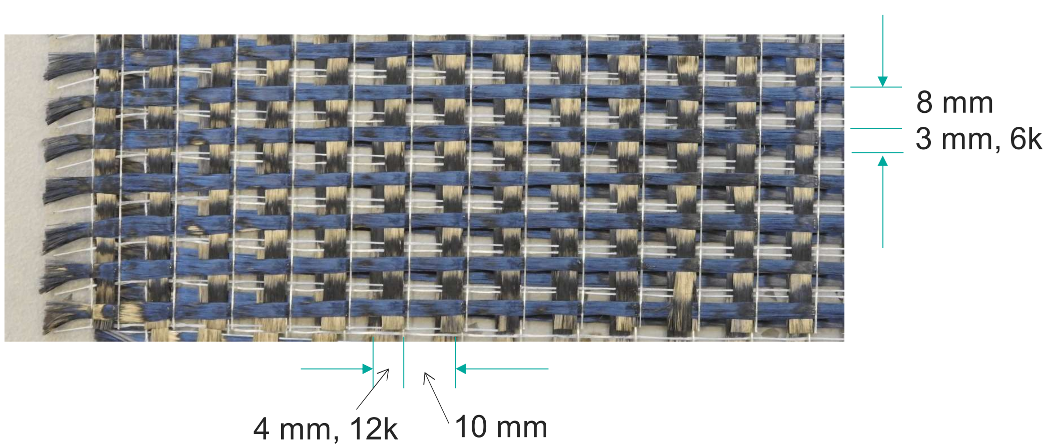
Carbon fiber mesh from China

(How to improve adhesion between **carbon fiber mesh** and concrete?)



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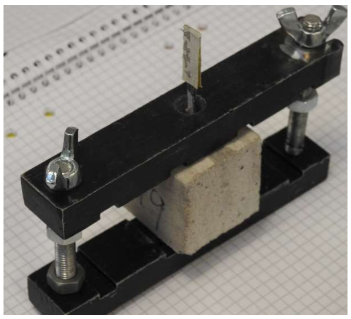
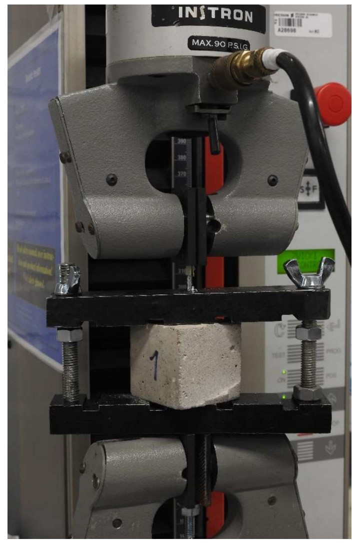
Pull-out Test of a Single Bundle

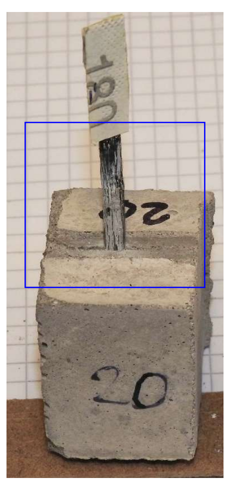


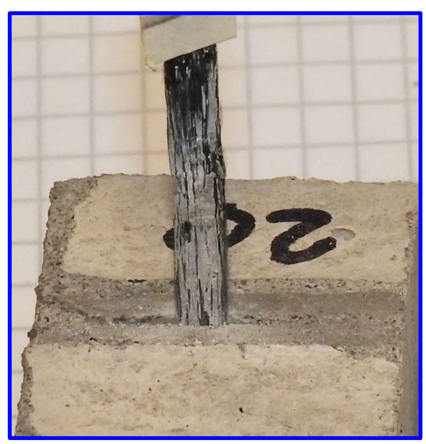
Specimen on the frame



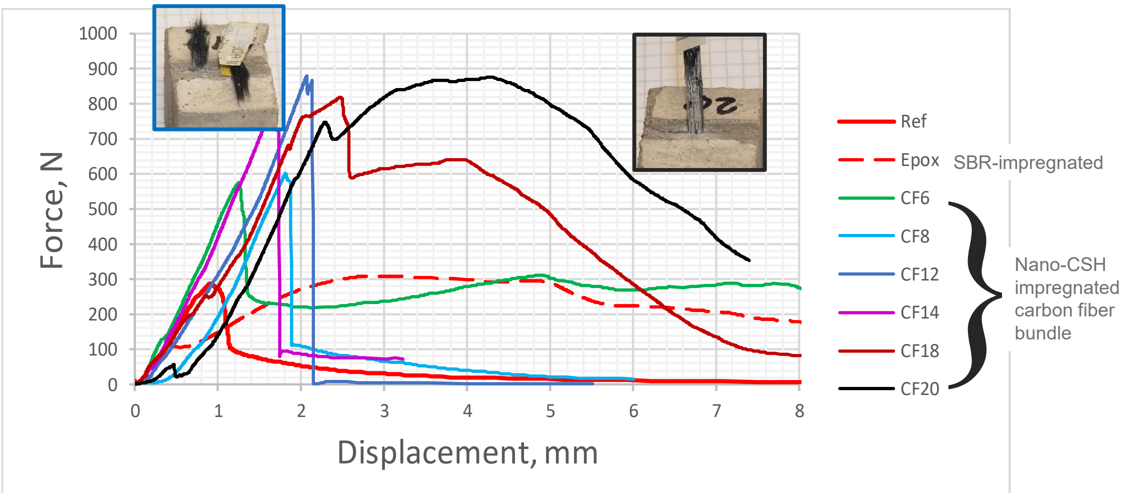
Pull-out test

Fibers after the pull-out test





Results from Pull-out Test



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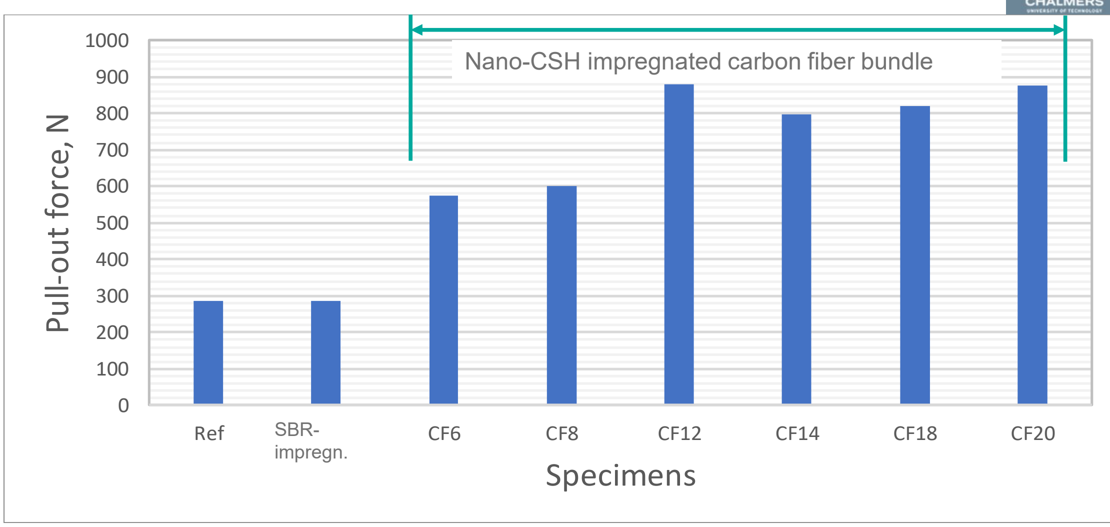
Pull-out Forces (average of two samples)



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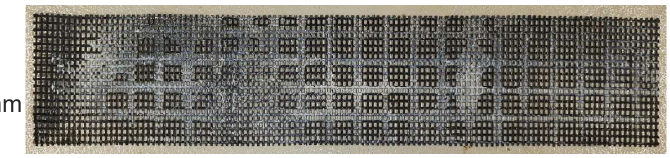
Nano Impregated Carbon Fiber Mesh



Prism 160x40x40 mm

Large plate 900x200x20 mm

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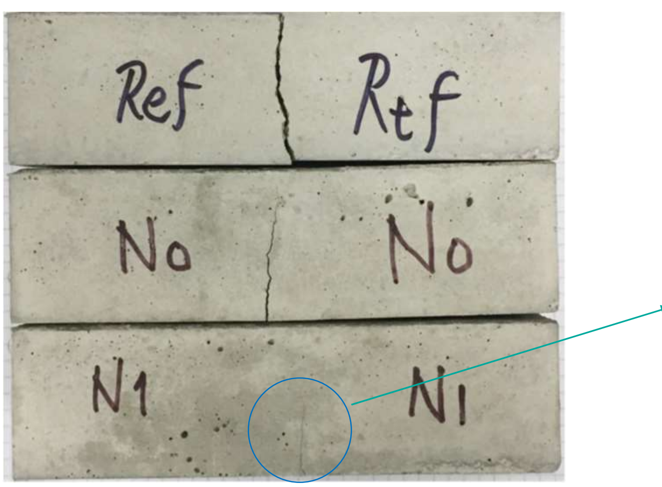
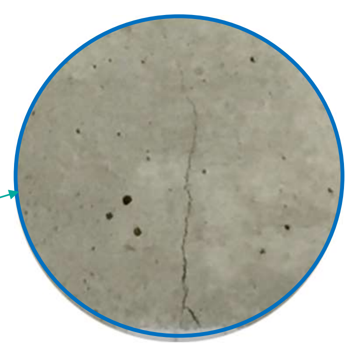
Cracks after 1st Bending Test (OPC)



Ref: No fiber mesh
N0: Original fiber mesh
N1: Nano-CS treated fiber mesh



Crack wideness 0.12 mm

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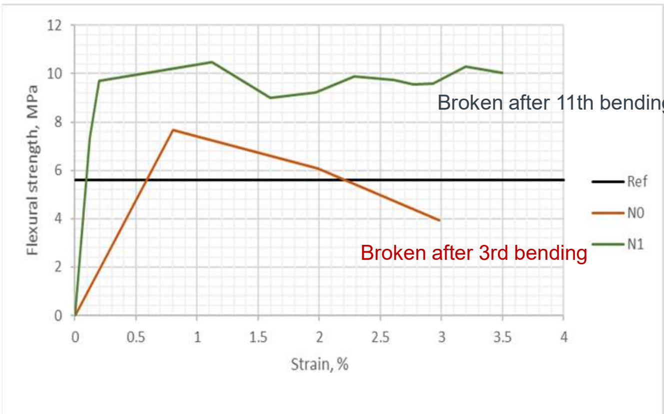
Results from Prisms with OPC

CHALMERS



Ref: No fiber mesh
N0: Original fiber mesh
N1: Nano-CS treated fiber mesh

- Dramatically increase the bonding between fibers and cementitious materials
- Significantly increase the flexural strength
- Significantly increase the ductility

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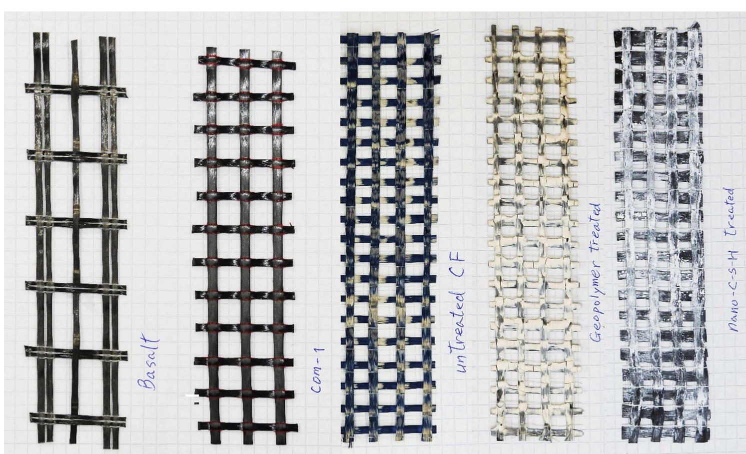
Five Different Types of Fiber Meshs

CHALMERS



Resin-impregnated basalt fiber | SBR impregnated carbon fiber | Original carbon fiber from China | Geopolymer impregnated carbon fiber | Nano-CSH impregnated carbon fiber

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Casting Fiber Mesh Prisms

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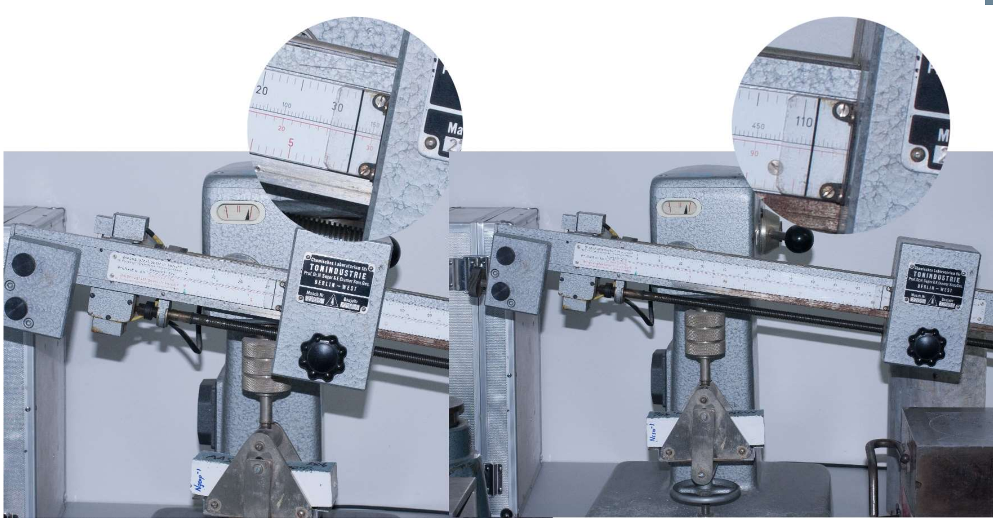
3-Point Bending Tests



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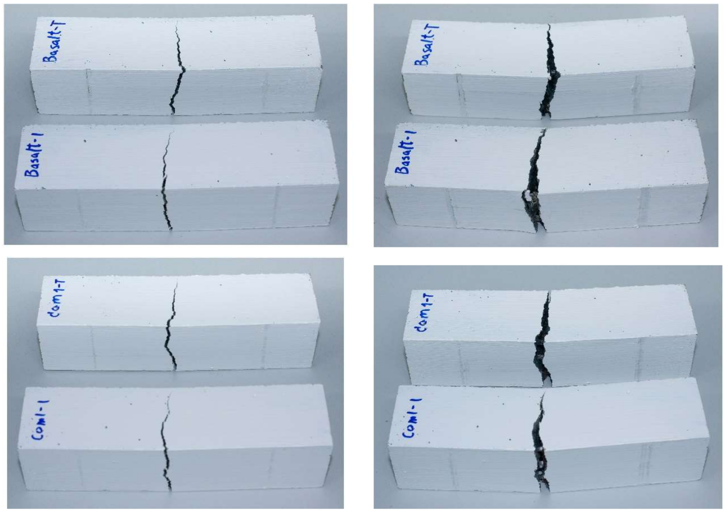
Industrial meshs after 1st & 4th bending



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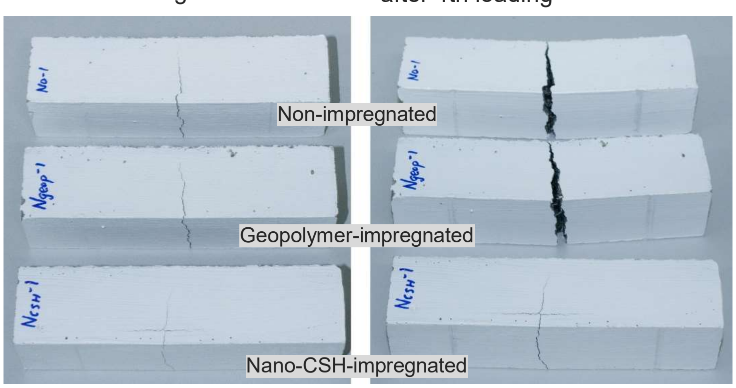
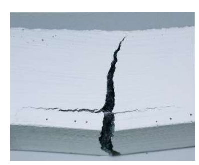
Impregnated Meshs after *n*-th Bending

after 1st loading

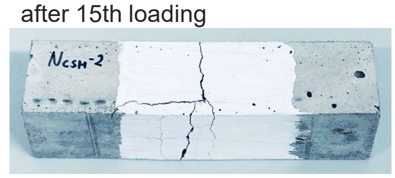
after 4th loading



after 10th loading Ncsh-1



after 15th loading



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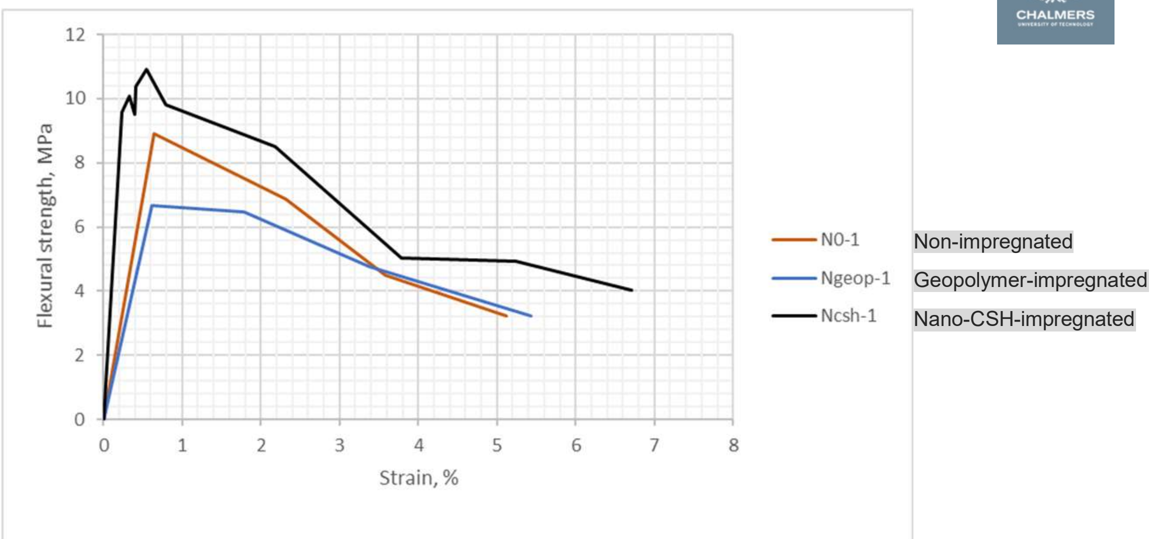
Strength-Strain Curves



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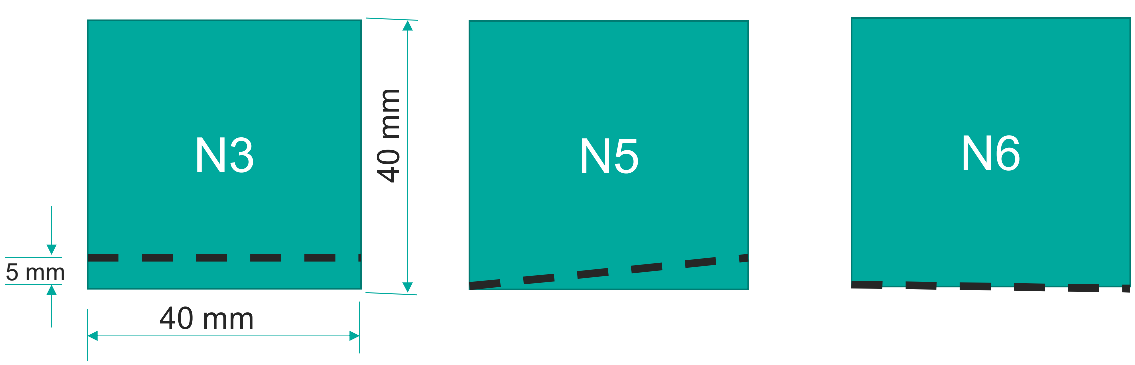
Locations of Mesh in ASS Prisms



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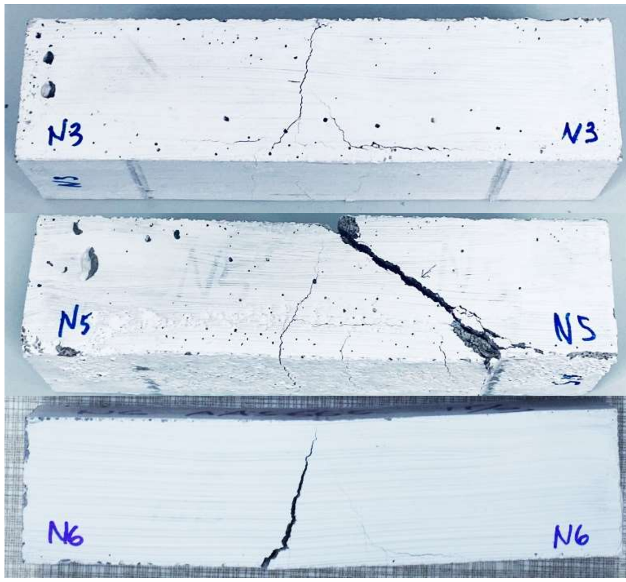
After *n*-th Loading



After 15th loading (max. loading)

After 20th loading

After 3rd loading

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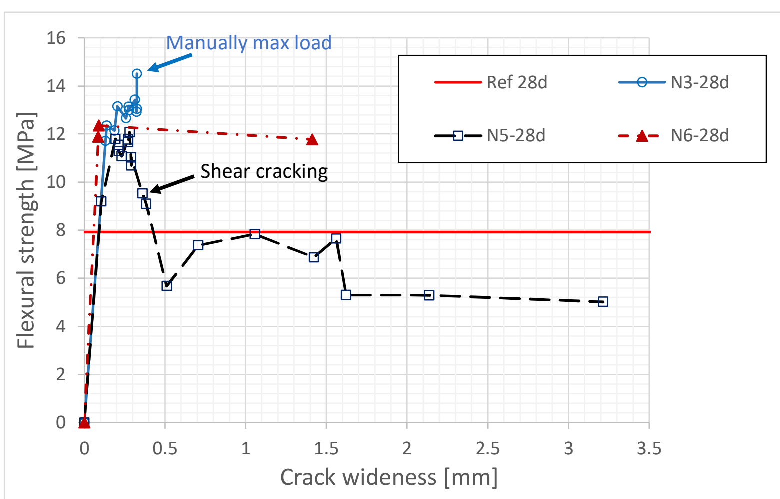
Strength-Crack Curves after n-th Bending



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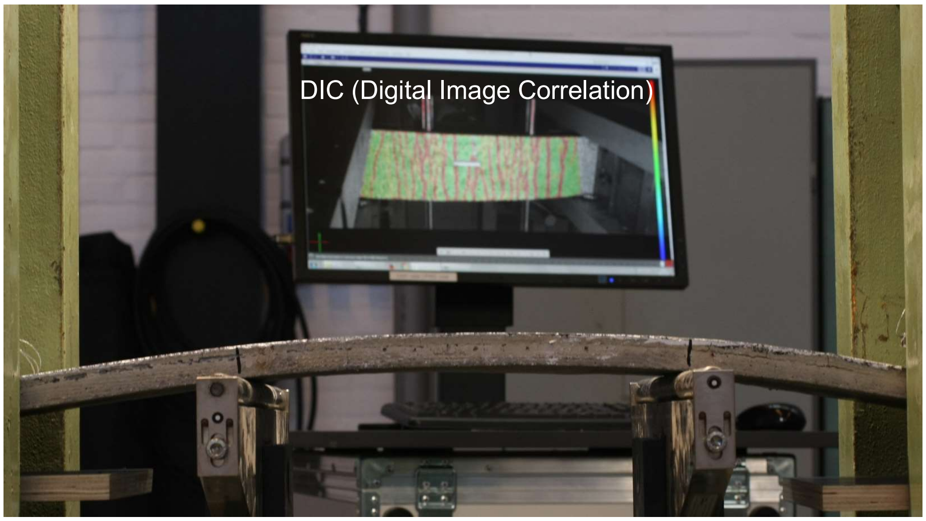
Large Plate under 4-P Bending Test



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Deformation of Large Plate under Bending

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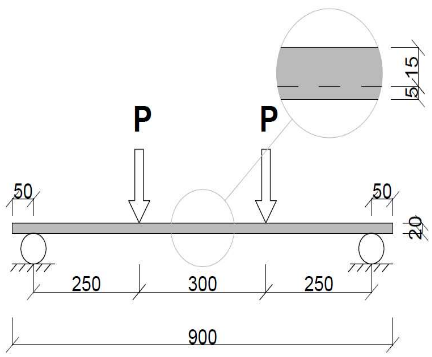
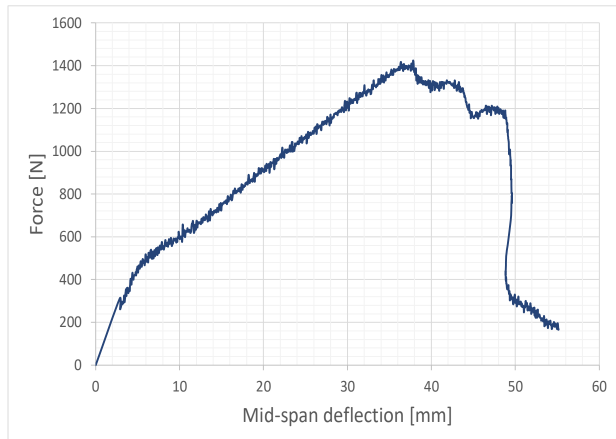
Results form 4-Point Bending Test





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Concluding Remarks on AAS Concrete

- The main contributor to the strength of alkali-activated slag (AAS) materials is alkali (Na_2O in this study), whilst the addition of molecular silica contributes to the strength by 30% of that of alkali;
- Addition of gypsum negatively contribute to the strength but positively contribute to the reduction of shrinkage;
- Partial addition of ordinary Portland cement (OPC) and/or gypsum can markedly reduce drying shrinkage of AAS materials;
- A combination of 20% OPC and 5% gypsum can reduce the drying shrinkage of AAS at the early age (about 10 days) to a level similar to hardened OPC;
- AAS showed a better resistances to chloride ingress and acid attack, as well as better stability under high temperatures.

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Concluding Remarks on Nano-Impregnated Carbon Fiber

- Increased bonding with concrete by a factor of 2-3;
- Concrete reinforced by nano-impregnated carbon fiber mesh revealed good loading capacity with shear failure, similar as over-sized steel reinforcement.
- It is possible to produce bendable concrete plate with nano-impregnated carbon fiber mesh.

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