20 Marzo 2019

UNIVERSITÀ DI PAVIA

Dissertation submitted for the degree of
Doctor of Philosophy
Supervisor: Prof. Ing. Ferdinando Auricchio

3D Concrete Printing:
a new Era in Construction Industry

UNIVERSITÀ DI PAVIA

In collaboration with

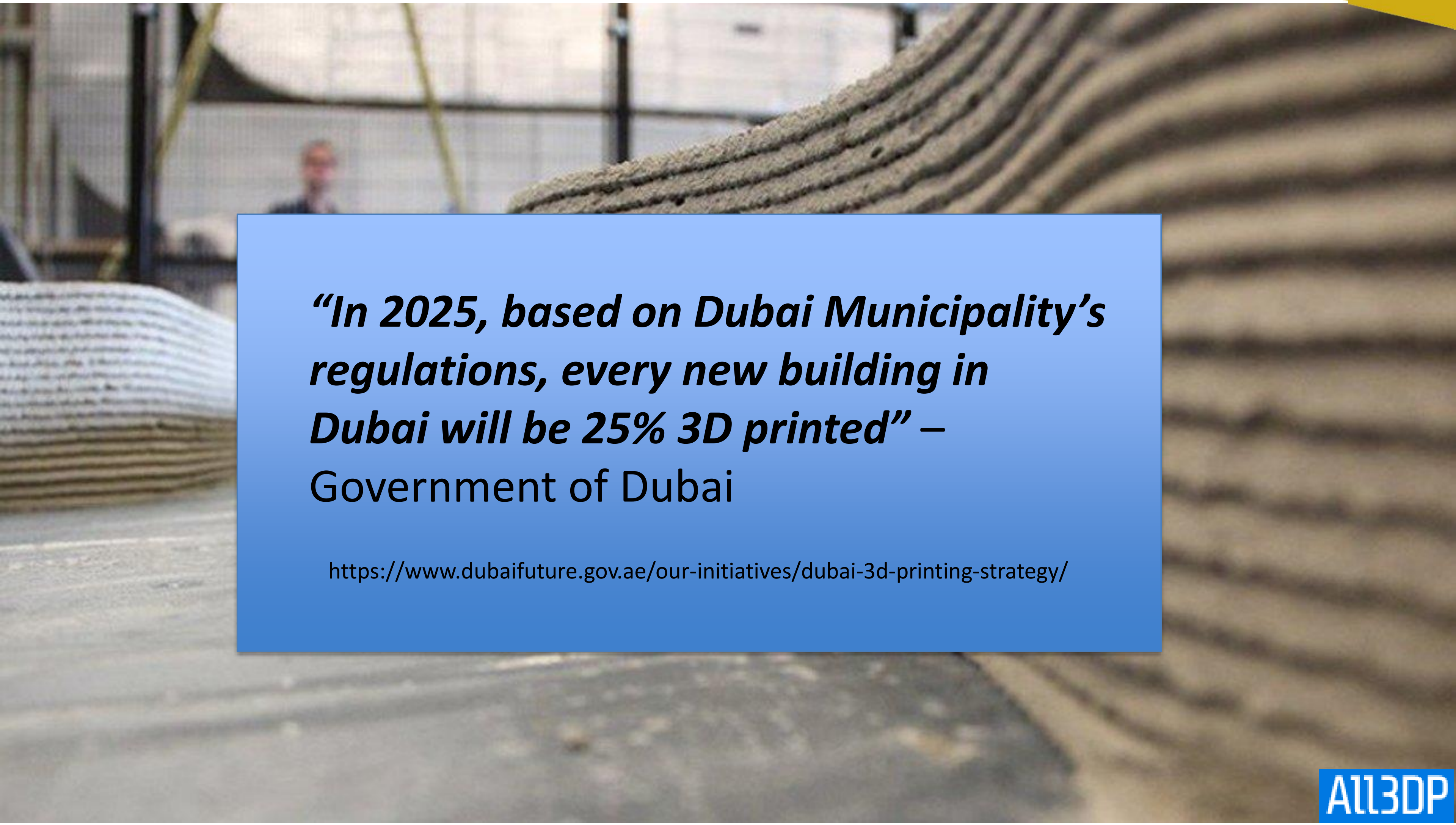
Università degli Studi di Napoli Federico II

Italcementi HEIDELBERGCEMENT Group

Outline

- Motivation
- Objectives
- Potentials and challenges
- A 3D printable concrete mix
  - Testing programme
    - Uniaxial unconfined compression testing
      - Analytical failure predictive model
    - Creep testing
    - Rheological testing
- Conclusions

Motivation



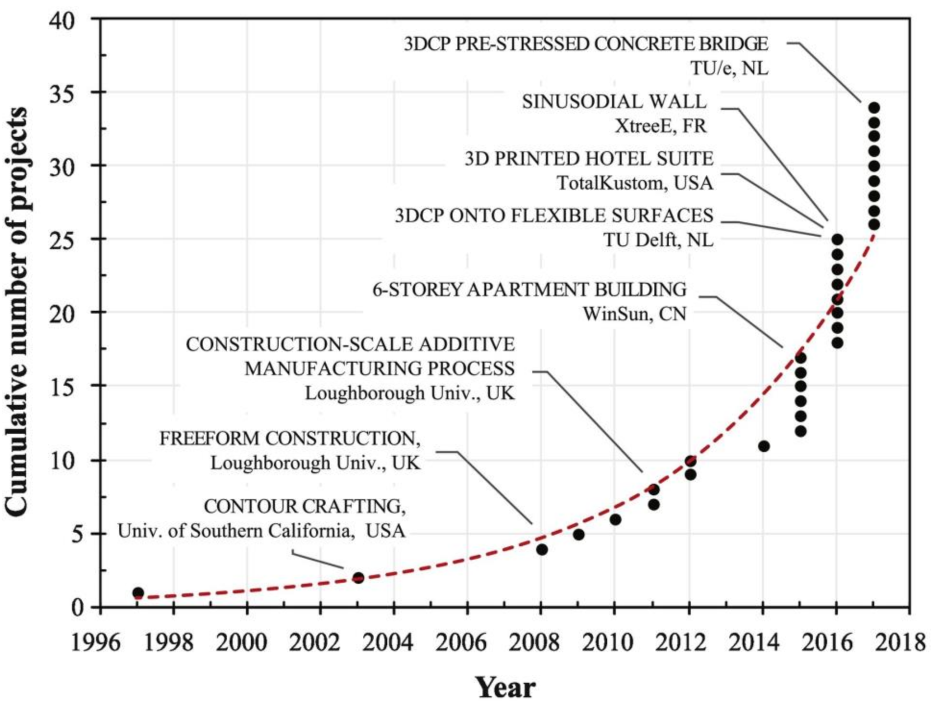
"In 2025, based on Dubai Municipality's regulations, every new building in Dubai will be 25% 3D printed" – Government of Dubai

https://www.dubaifuture.gov.ae/our-initiatives/dubai-3d-printing-strategy/

Motivation

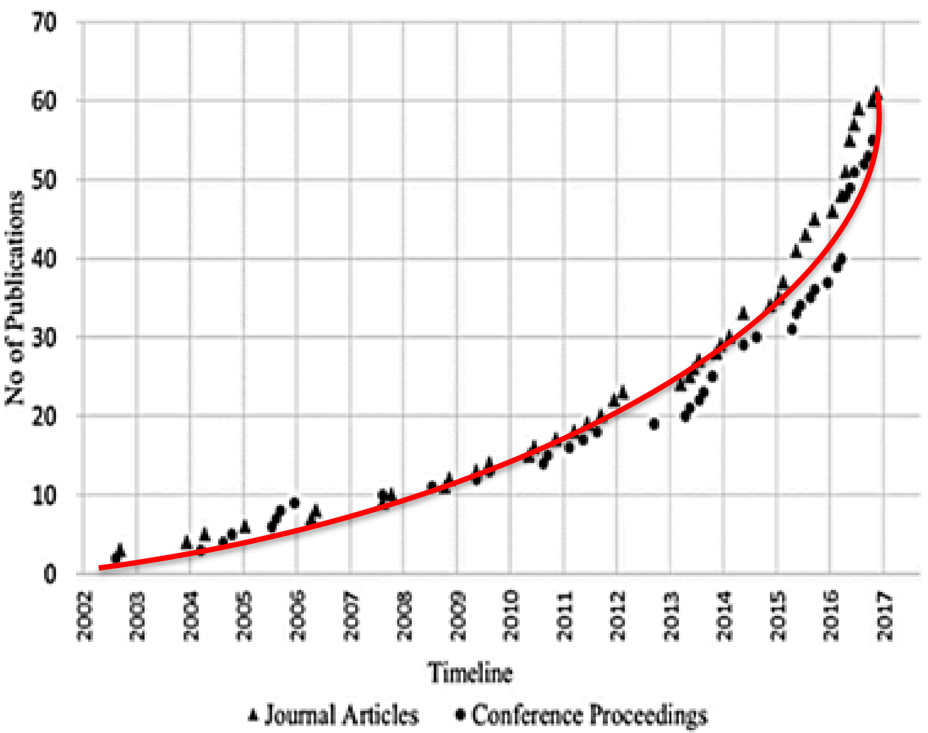
3D Concrete Printing trend

Number of projects over the years



[1] BUSWELL, Richard A., et al. 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research*, 2018, 112: 37-49.

Number of publications over the years



[2] TAY, Yi Wei Daniel, et al. 3D printing trends in building and construction industry: a review. Virtual and Physical Prototyping, 2017, 12.3: 261-276.

Motivation

A robust **3D CONCRETE PRINTING** process consists in optimizing the **MATERIAL** compatibility with the **PRINTING SYSTEM**

Rheological and mechanical properties of 3D printed materials exhibit dualities

An EXPERIMENTAL INVESTIGATION is necessary to define mechanical properties of the material

The need to define a STANDARD PROCEDURE is indisputable

- Early age printable mortars differ from classical casting concrete
- Strength and stiffness evolve in time
- Microstructural changes occur during cement hydration

Objectives

GOAL

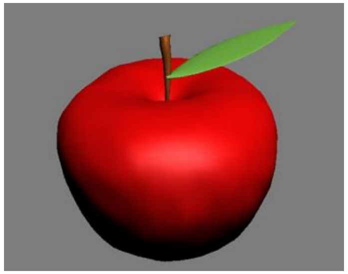
Demonstrate need in a ***standard procedure*** for 3D printable concrete mix: experimental results compared by varying testing procedures, investigating the effect of such variations on mechanical properties

Testing campaign on fresh concrete

[3] CASAGRANDE, Lorenzo, et al. Effect of testing procedures on buildability properties of 3D-printable concrete. Construction and Building Materials, 2020, 245: 118286.

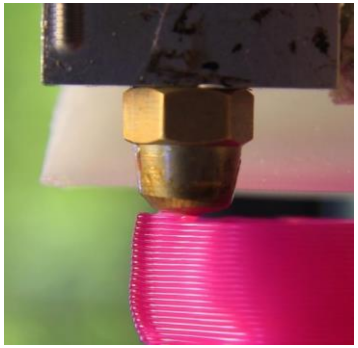
Basic concepts

3D PRINTNG PROCEDURE



Virtual modeling

Slicing



3D Printing

3D Printed object!

What about construction industry?

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Potentials and Challenges

POTENTIALS:

- ✓ reduction in construction time and cost
- ✓ increase in worker safety
- ✓ potential of freeform architectures, better quality and reliability
- ✓ environmental benefits due to the saving of material waste

CHALLENGES:

- χ larger machines required
- χ control of phase transition
- χ implementation of reinforcement
- χ optimization of specific early age mechanical and rheological properties (Workability, Extrudability, Buildability)

Experimental exploration of FRESH 3D printable cementitious materials

Objectives

GOAL

Demonstrate need in a ***standard procedure*** for 3D printable concrete mix: experimental results compared by varying testing procedures, investigating the effect of such variations on mechanical properties

STEPS

1. design a 3D printable concrete mix
2. define the testing programme
3. develop a standard procedure for uniaxial unconfined compression test
4. provide an analytical failure predictive model
5. define a standard method for creep test
6. provide a standard procedure for rheological test

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Virtual Modeling and Additive Manufacturing for Advanced Materials

3D printable concrete mix

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Meet specific performance requirements in both **FRESH** and **HARDENED STATE**

FRESH STATE: optimised balance between ***workability***, ***extrudability*** and ***buildability***
HARDENED STATE: linked to material ***strength*** and ***stiffness*** properties

1. Workability
mixing and pumping throughout a reasonable time interval

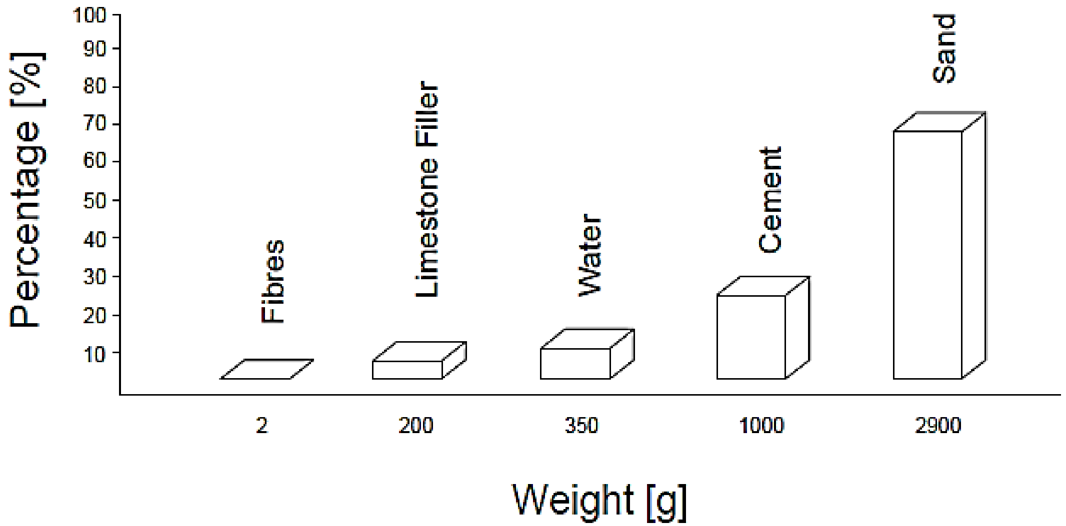
2. Extrudability
extrusion with a continuous material flow

3. Buildability
remain stacked in layers after extrusion and sustain the weight

3D printable concrete mix

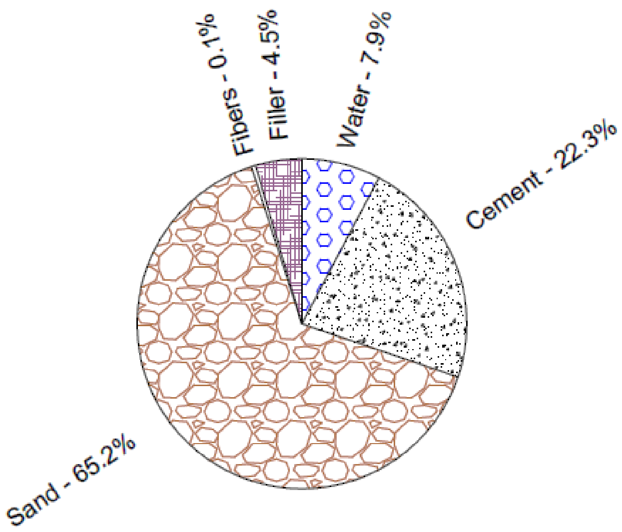
CEM type I 42.5N [4]
Low W/b = 0.35
limestone fillers (*$CaCO_3$*)
Polypropylene fibres

Slump class, S1, 14 ± 2 mm
Cubic strength, R_{cm}, 53.5 MPa
Cylindrical strength, f_{cm}, 44.4 Mpa



SuperPlasticizer (SP): 0.1% of cement weight

Variations used to determine changes in material consistency during the printing process



[4] ASPRONE, Domenico, et al. 3D printing of reinforced concrete elements: Technology and design approach. Construction and Building Materials, 2018, 165: 218-231.

Objectives

GOAL

Demonstrate need in a ***standard procedure*** for 3D printable concrete mix: experimental results compared by varying testing procedures, investigating the effect of such variations on mechanical properties

STEPS

1. design a 3D printable concrete mix
2. define the testing programme
3. develop a standard procedure for uniaxial unconfined compression test
4. provide an analytical failure predictive model
5. define a standard method for creep test
6. provide a standard procedure for rheological test

Testing programme

Workability, extrudability, buildability are related to physical properties of fresh mortars by:

Time-dependent

- ***layer cycle-time***, time required to complete one build layer → Compressive strength and stiffness — **COMPRESSIVE TESTS**
- ***deformation*** of material as successive layers are added → self-weight and creep strain — **CREEP TESTS**
- ***open time***, time during which a material may be used in 3D printing → plastic viscosity and yield stress, — **RHEOLOGICAL TESTS**

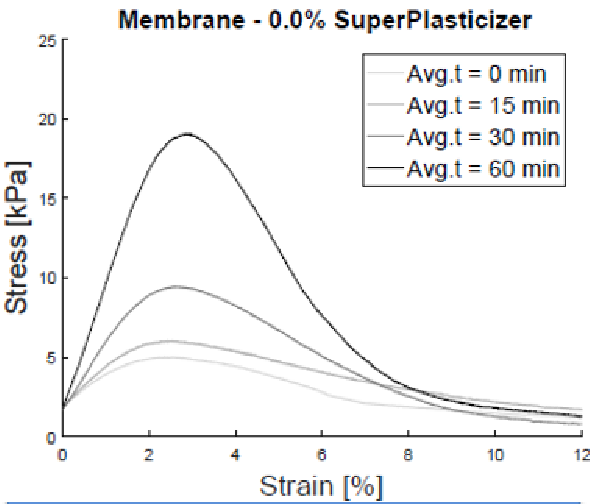
[1] BUSWELL, Richard A., et al. 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research*, 2018, 112: 37-49.

Testing programme

Tests performed @Unipv

Uniaxial Unconfined Compression Tests

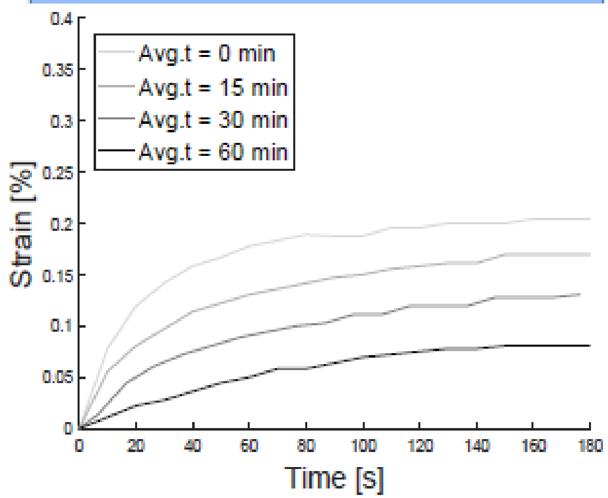
120 TESTS



Influence of:
- Sample Age
- SuperPlasticizer
- Membrane
- Displacement rate

Creep Tests

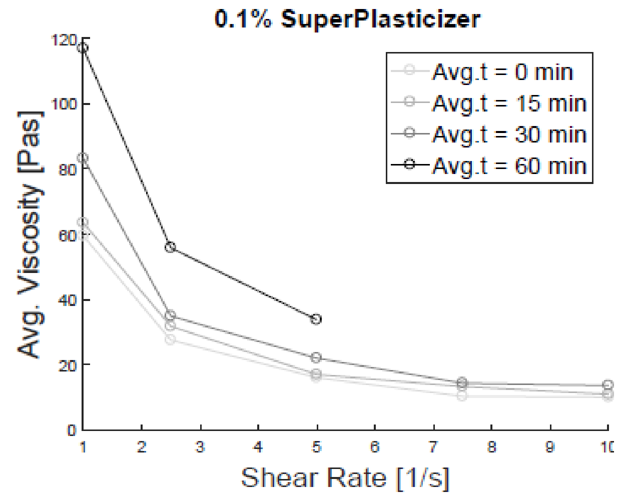
140 TESTS



Influence of:
- Sample Age
- SuperPlasticizer
- Displacement rate
- Duration

Rheological Tests

40 TESTS



Influence of:
- Sample Age
- SuperPlasticizer
- Shear Rate

Objectives

GOAL

Demonstrate need in a ***standard procedure*** for 3D printable concrete mix: experimental results compared by varying testing procedures, investigating the effect of such variations on mechanical properties

STEPS

1. design a 3D printable concrete mix
2. define the testing programme
3. develop a standard procedure for uniaxial unconfined compression test
4. provide an analytical failure predictive model
5. define a standard method for creep test
6. provide a standard procedure for rheological test

Compression tests

We performed a sensitivity analysis considering:

- ***Evolution over time***: strength and stiffness of early-age concrete changes during the printing process
- ***Materials and sample preparation***: during 3D printing process, it is possible to experience variations in the workability of the material
- ***Compressive test set-up***: 3D printable concrete behaves as a visco-plastic Bingham material, response is affected by sample size/loading rate

VARIATIONS

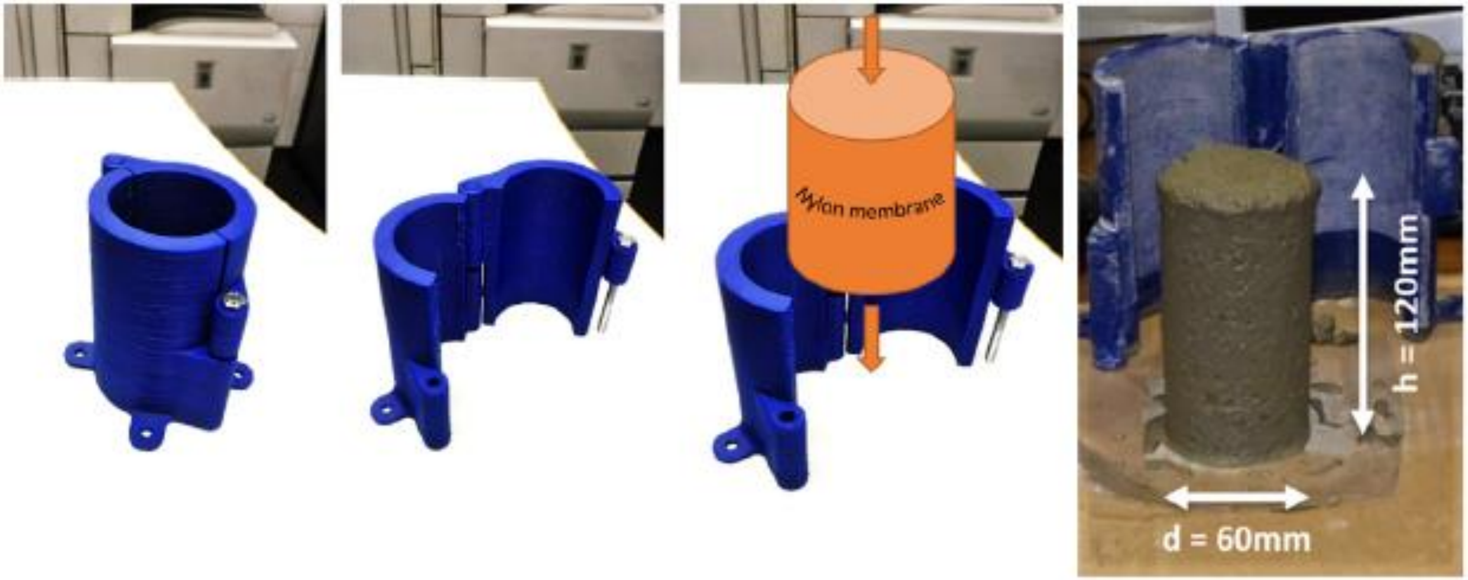
1. UUCTs at distinct **CONCRETE AGES**
   t = 0, 15, 30 and 60 min
2. UUCTs at distinct **SUPERPLASTICIZER AMOUNT**
   SP = 0.0, 0.1, 0.15%
3. **SAMPLE PREPARATION**
   Membrane = yes/no
4. UUCTs at distinct **DISPLACEMENT RATE**
   Dr = 3mm/min vs 30mm/min

Compression tests

SAMPLE PREPARATION

Challenges during specimen preparation due to very early age of the material (i.e. casting, compaction, demoulding)

To overcome this issue, we designed a **plastic 3D-printed openable mould** to reproduce cylindrical specimens with good shape retention.

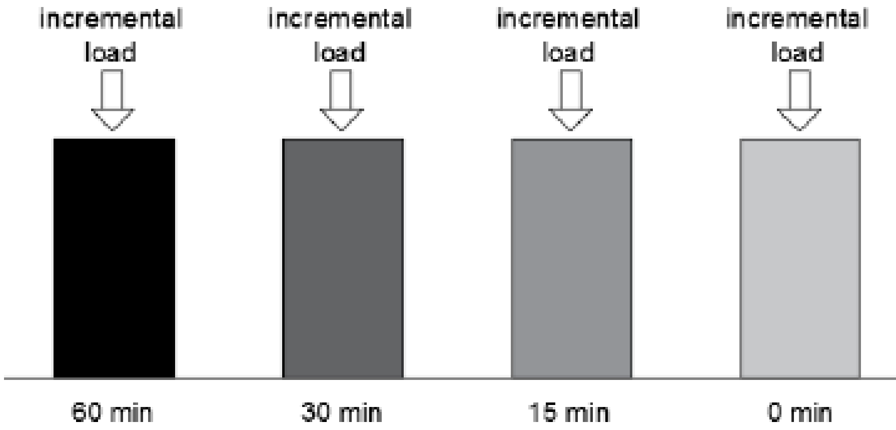


[3] CASAGRANDE, Lorenzo, et al. Effect of testing procedures on buildability properties of 3D-printable concrete. Construction and Building Materials, 2020, 245: 118286.

Compression tests

Test protocol

- Displacement-control condition
- Room temperature T = 22°C
- Max strain 12%, i.e. 15 mm in displacement.



Stress and strain deduced from force-displacement diagrams.
Young's modulus is computed as secant modulus from 0% to 2% of the strain.

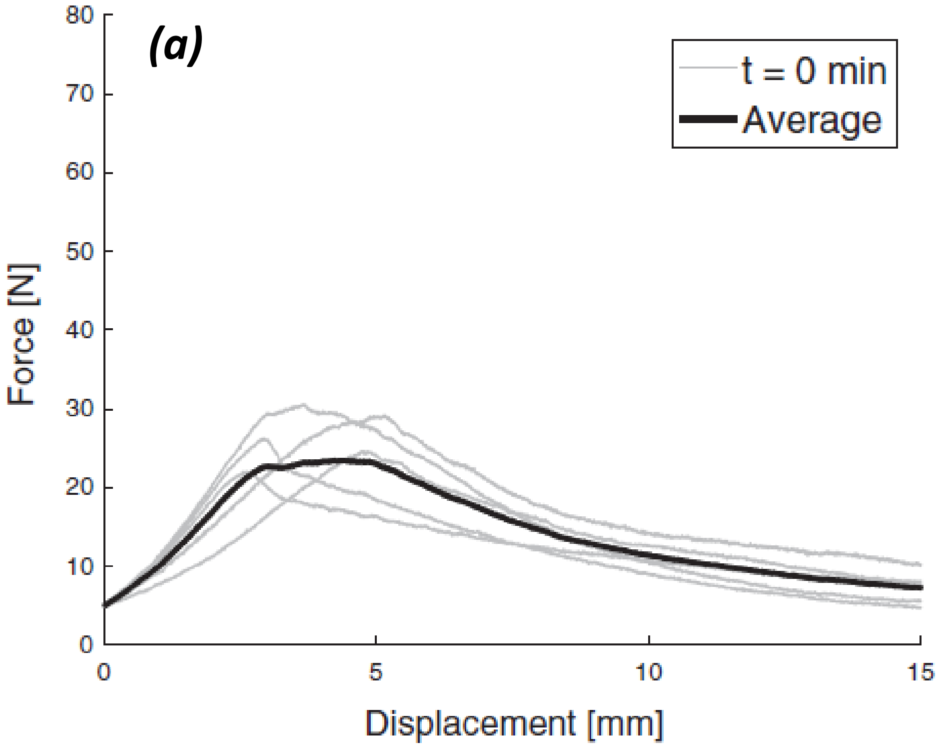
Variables	Uniaxial unconfined compression tests					
Acronym	REF-SP0.10-M-DR3	SP0.00-M-DR3	SP0.15-M-DR3	SP0.00-NM-DR3	SP0.10-NM-DR3	SP0.10-M-DR30
1. Age [min]	0, 15, 30, 60	0, 15, 30, 60	0, 15, 30, 60	0, 15, 30, 60	0, 15, 30, 60	0, 15, 30, 60
2. Superplasticizer [%]	0.1	0.0	0.15	0.0	0.1	0.1
3. Membrane	Yes	Yes	Yes	No	No	Yes
4. Displacement rate [mm/min]	3.0	3.0	3.0	3.0	3.0	30.0
Samples per set	5	5	5	5	5	5
Tot. samples	20	20	20	20	20	20

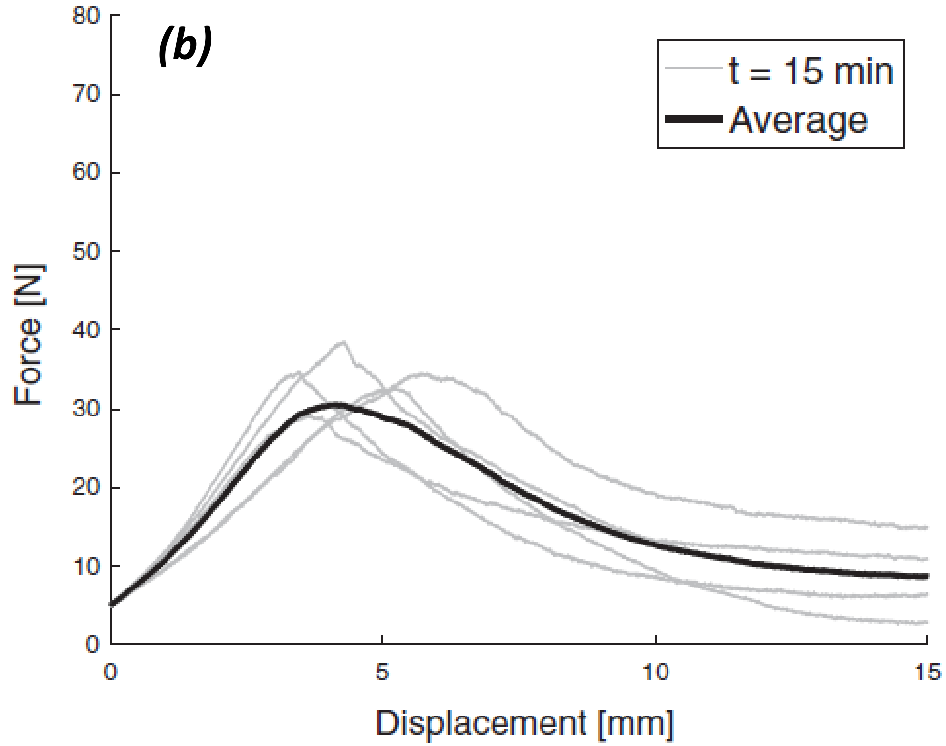
reference test
REF-SP0.10-M-DR3
"SPxx-yM-DRzz"

Test matrix.

[3] CASAGRANDE, Lorenzo, et al. Effect of testing procedures on buildability properties of 3D-printable concrete. Construction and Building Materials, 2020, 245: 118286.

Compression tests

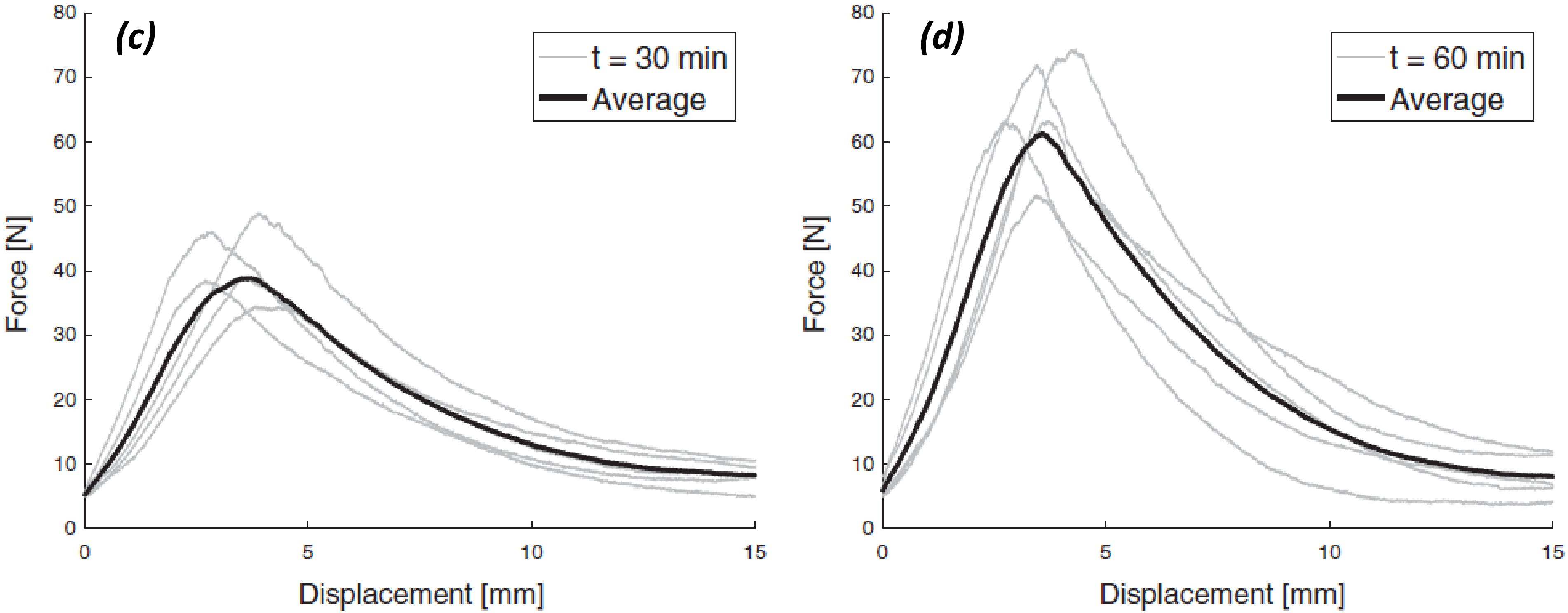




***Effect of Age*: REF-SP0.10-M-DR3.**
Average and individual results at different times: (a) 0 min, (b) 15 min.

- As samples were not perfectly flat, forces began to stabilize around 5 N

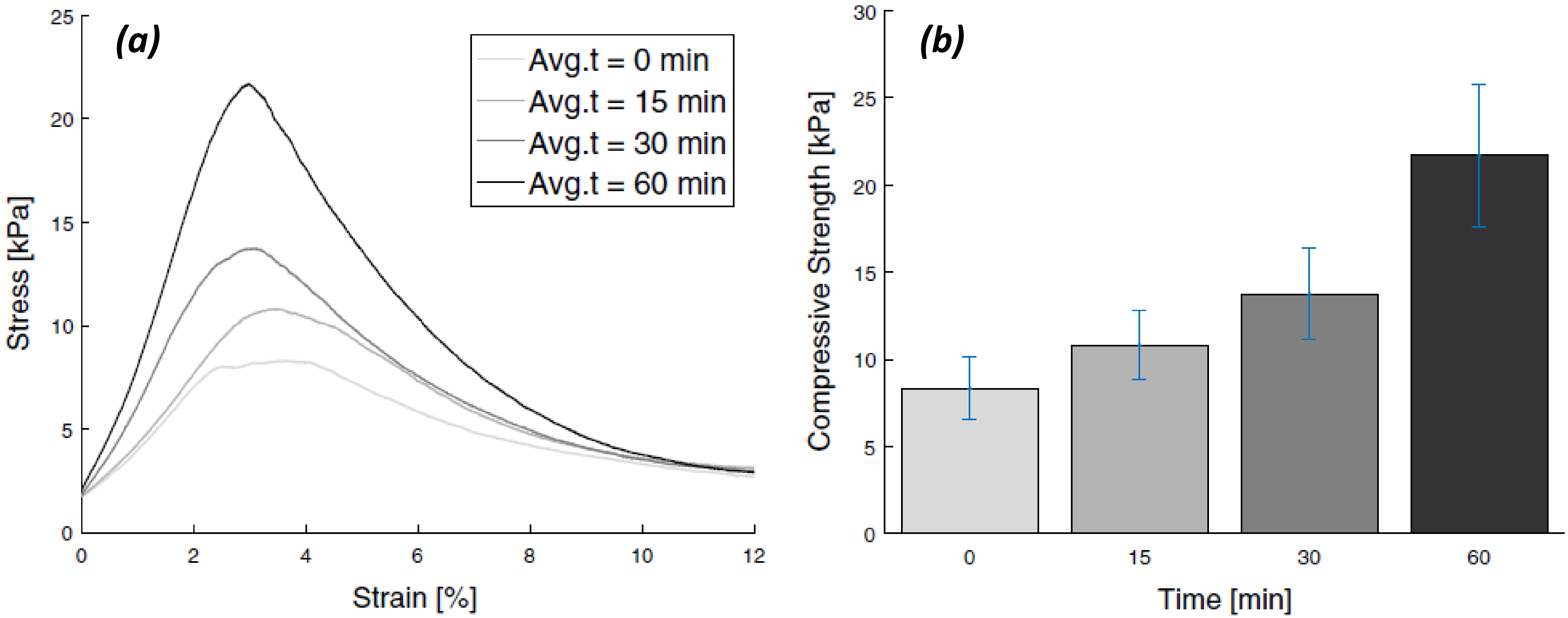
Compression tests



Effect of Age ***: REF-SP0.10-M-DR3.***
Average and individual results at different times: (c) 30 min, (d) 60 min.

- Softening is more evident for older specimens (30 and 60 min) respect to younger ones (0 and 15 min)

Compression tests

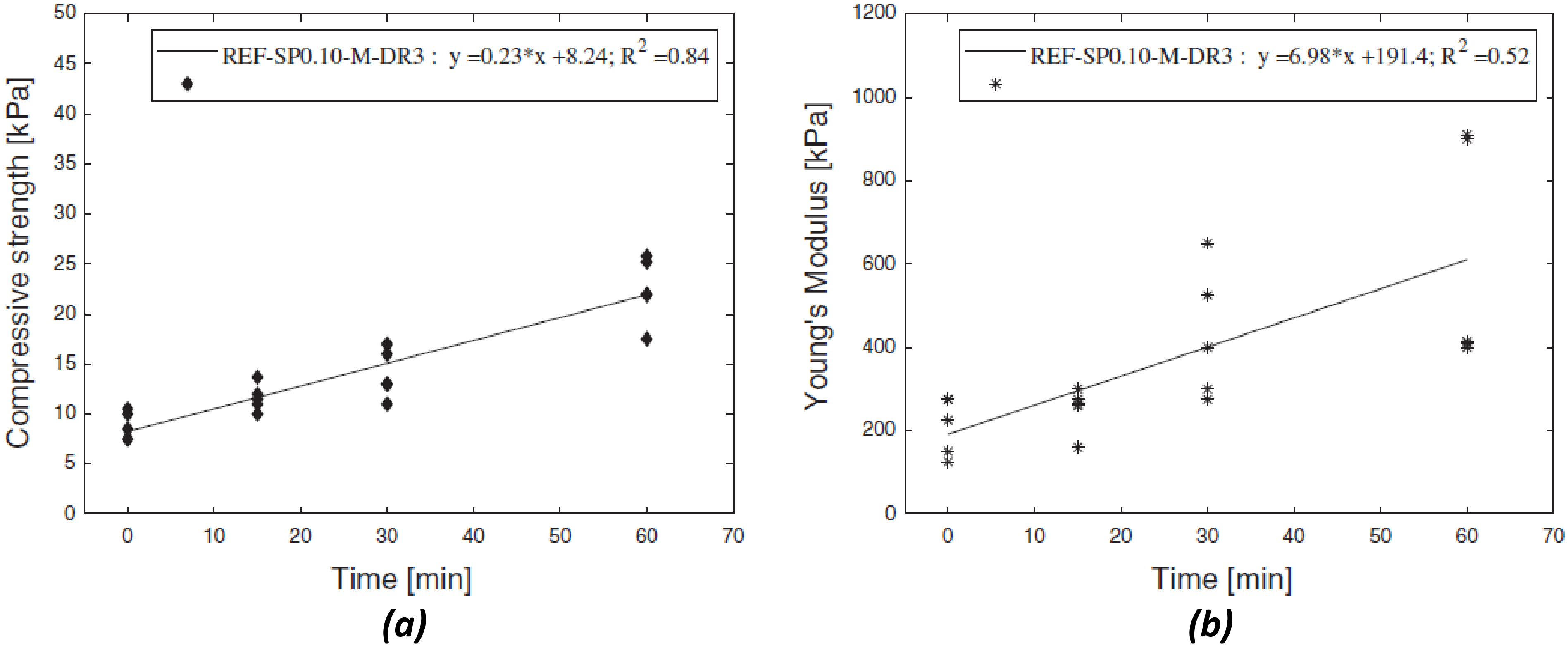


Effect of Age ***: REF-SP0.10-M-DR3.***

Average comparison: (a) stress-strain curves, (b) compressive strength and standard deviation

- Peak value (compressive strength $\sigma_{c,max}$) after initial linear-elastic behaviour
- Strain limit of the elastic range was about 2.5%

Compression tests



***Effect of Age* : REF-SP0.10-M-DR3.**
Evolution over time of the compressive strength (a) and Young's modulus (b).

- Curing time increases compressive strength and stiffness

Compression tests

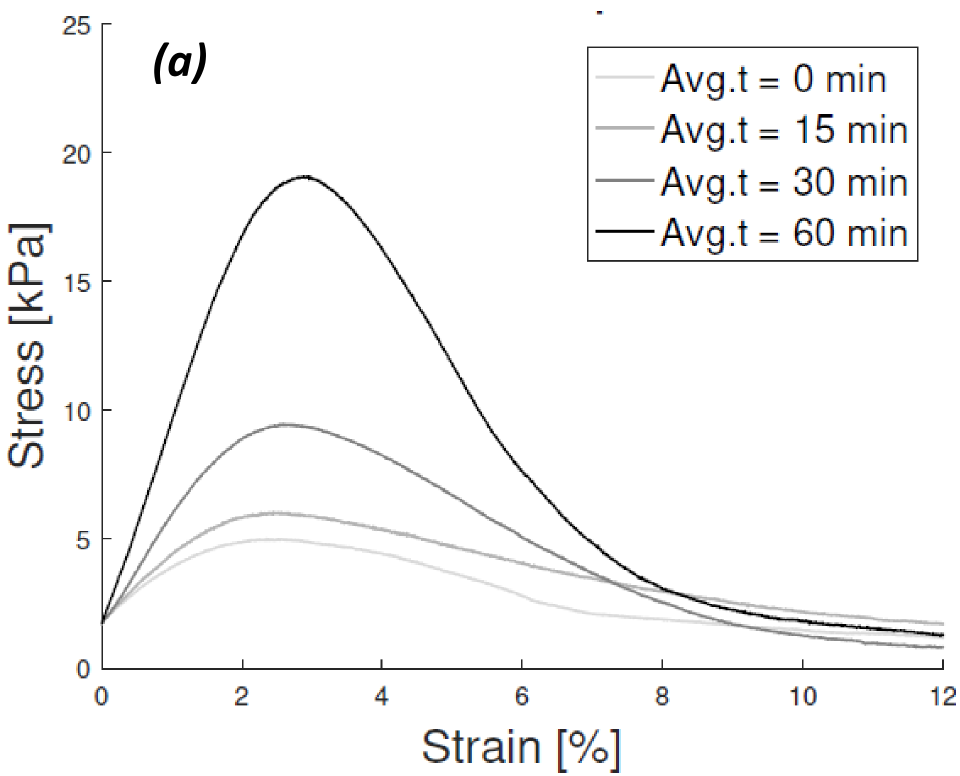
	Concrete Age			
	0 min	**15 min**	**30 min**	**60 min**
	Compressive Strength, σ			
REF-SP0.10-M-DR3	8.80 kPa	11.64 kPa	14.00 kPa	22.48 kPa
	RSD (σ)			
REF-SP0.10-M-DR3	15.87 %	11.76 %	17.49 %	14.72 %
	Young's Modulus, E			
REF-SP0.10-M-DR3	210 kPa	252 kPa	430 kPa	607 kPa
	RSD (E)			
REF-SP0.10-M-DR3	33.25 %	21.31 %	36.63 %	44.83 %

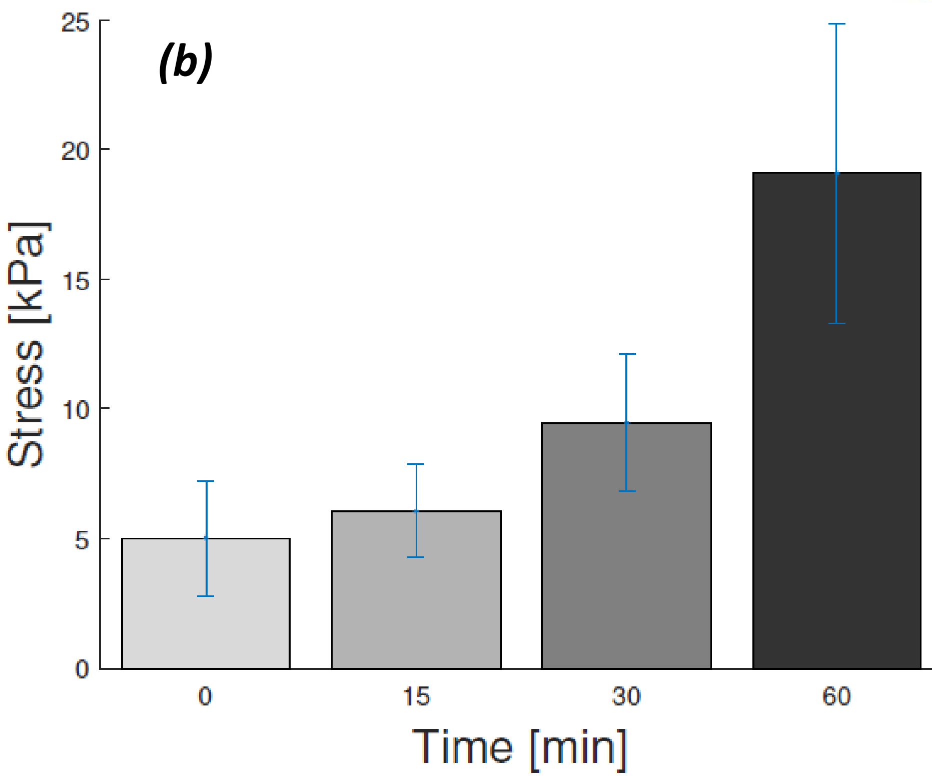
***Effect of Age*: REF-SP0.10-M-DR3.**

Average comparison: Compressive strength, Young's modulus and relative standard deviation

- From 0 to 60 min, compressive strength and stiffness increase by 156% and 189%

Compression tests



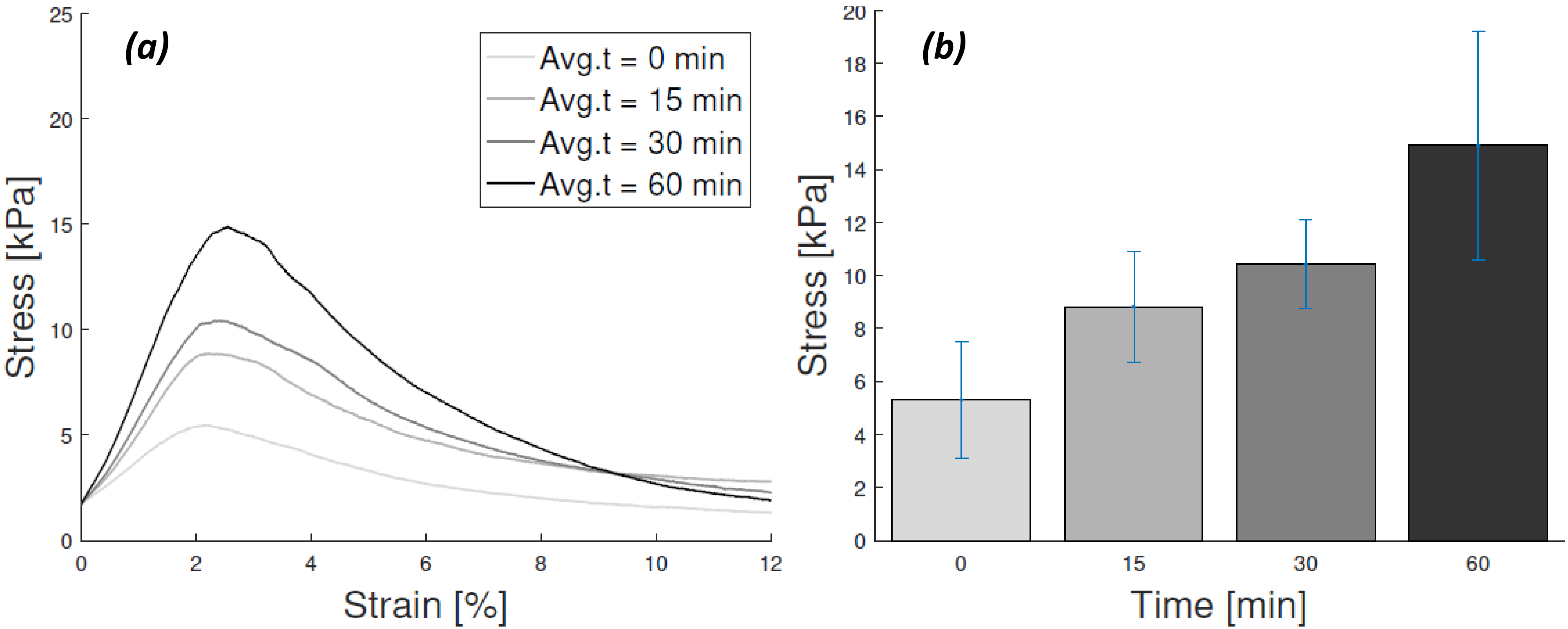


***Effect of SuperPlasticizer* : SP0.00-M-DR3.**

Average comparison: (a) stress-strain curves, (b) compressive strength and standard deviation

- During sample preparation, absence of SP resulted in a loss of workability
- Corresponding samples characterized by imperfections and voids

Compression tests

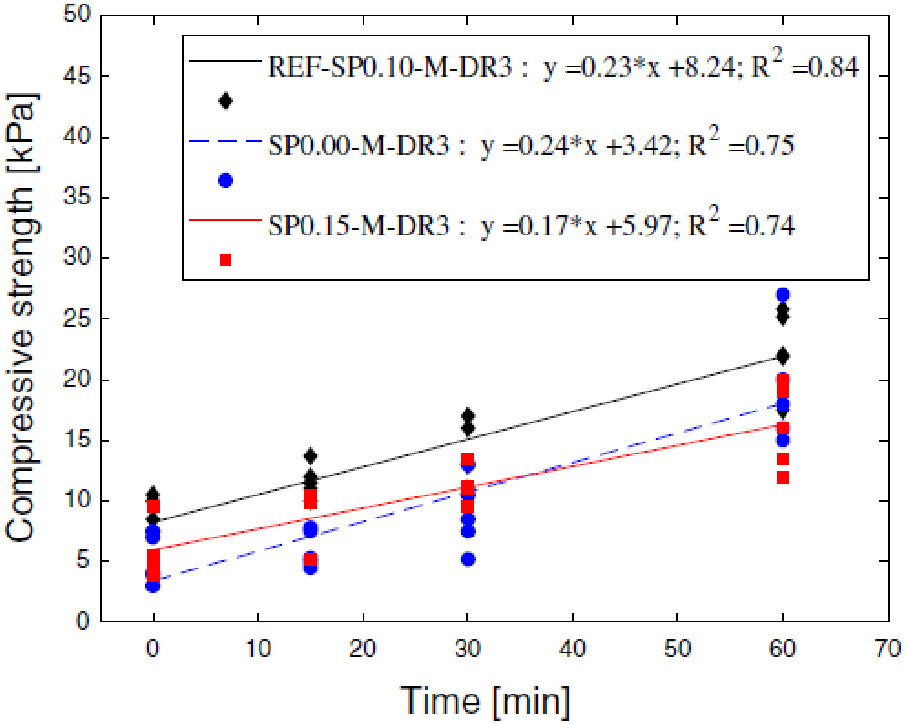


***Effect of SuperPlasticizer* : SP0.15-M-DR3.**

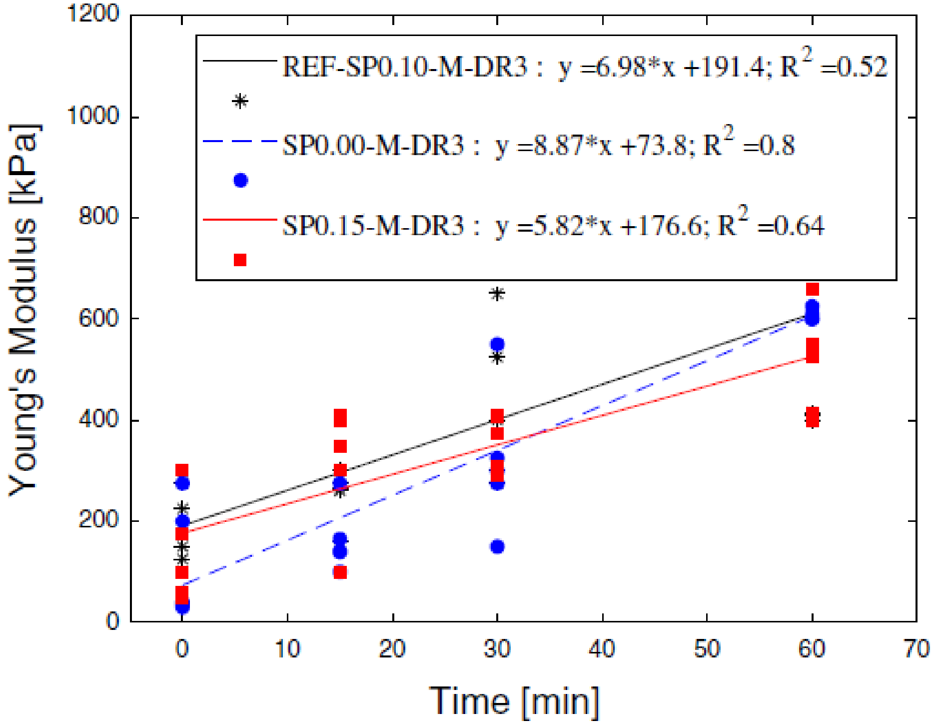
Average comparison: (a) stress-strain curves, (b) compressive strength and standard deviation

- Increments in the SP led to the excessive fluidity of the material
- Corresponding samples characterized by particle segregation

Compression tests



(a)



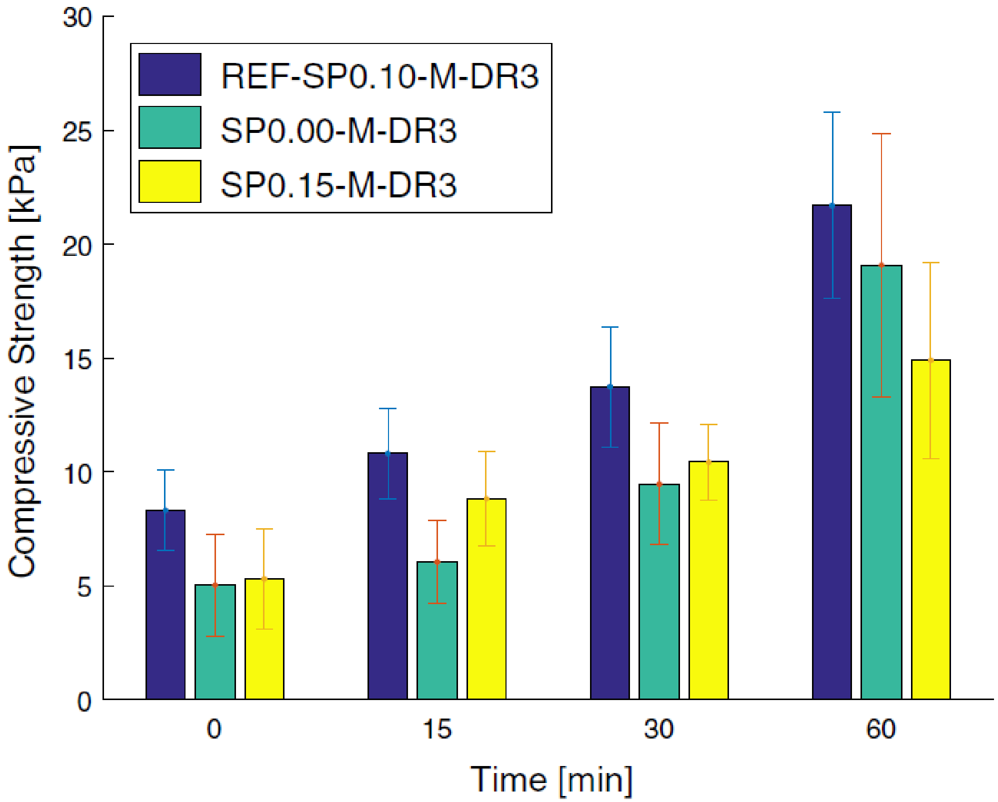
(b)

Effect of SuperPlasticizer

Evolution over time of the compressive strength (a) and Young's modulus (b).

- Mixes with 0.00% and 0.15% of SP produced lower mechanical performances (up to 40%), especially in terms of the compressive strength

Compression tests



Effect of SuperPlasticizer

Average comparison: compressive strength and standard deviation

- Mixes with too little or too much SP, had lower compressive strength and higher relative standard deviations

Compression tests

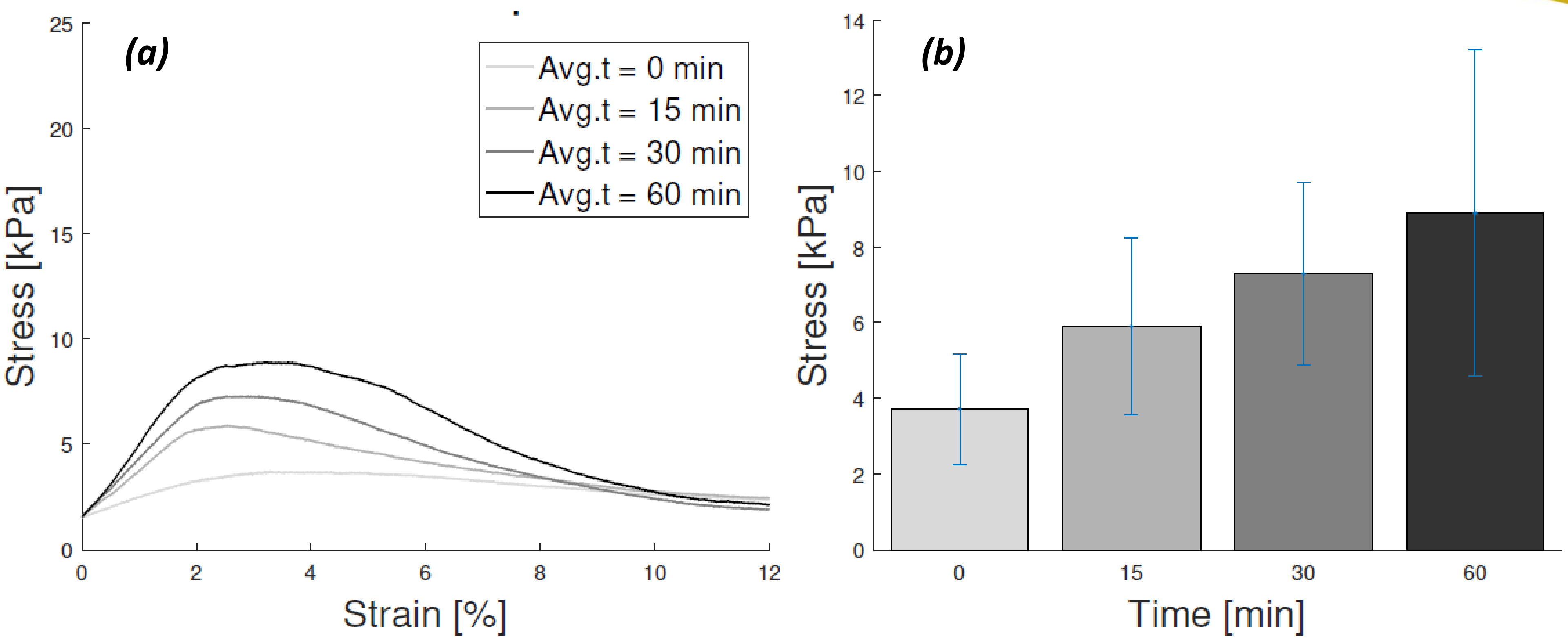
	Concrete Age			
	0 min	15 min	30 min	60 min
	Compressive Strength, σ			
REF-SP0.10-M-DR3	**8.80 kPa**	**11.64 kPa**	**14.00 kPa**	**22.48 kPa**
SP0.00-M-DR3	5.10 kPa	6.02 kPa	8.94 kPa	19.20 kPa
SP0.15-M-DR3	5.46 kPa	9.16 kPa	11.24 kPa	16.10 kPa
	RSD (σ)			
REF-SP0.10-M-DR3	**15.87 %**	**11.76 %**	17.49 %	**14.72 %**
SP0.00-M-DR3	39.46 %	25.23 %	33.17 %	25.82 %
SP0.15-M-DR3	43.08 %	24.35 %	**12.78 %**	21.34 %
	Young's Modulus, E			
REF-SP0.10-M-DR3	**210 kPa**	252 kPa	**430 kPa**	607 kPa
SP0.00-M-DR3	116 kPa	164 kPa	320 kPa	**627 kPa**
SP0.15-M-DR3	137 kPa	**312 kPa**	358 kPa	510 kPa
	RSD (E)			
REF-SP0.10-M-DR3	**33.25 %**	**21.31 %**	36.63 %	44.83 %
SP0.00-M-DR3	98.36 %	40.41 %	45.35 %	**6.71 %**
SP0.15-M-DR3	75.57 %	40.50 %	**15.38 %**	20.90 %

Effect of SuperPlasticizer

Average comparison: Compressive strength, Young's modulus and relative standard deviation

- At t = 0, relative standard deviation was 15.87% for reference test, and about 40% for 0.00% and 0.15% of SP

Compression tests

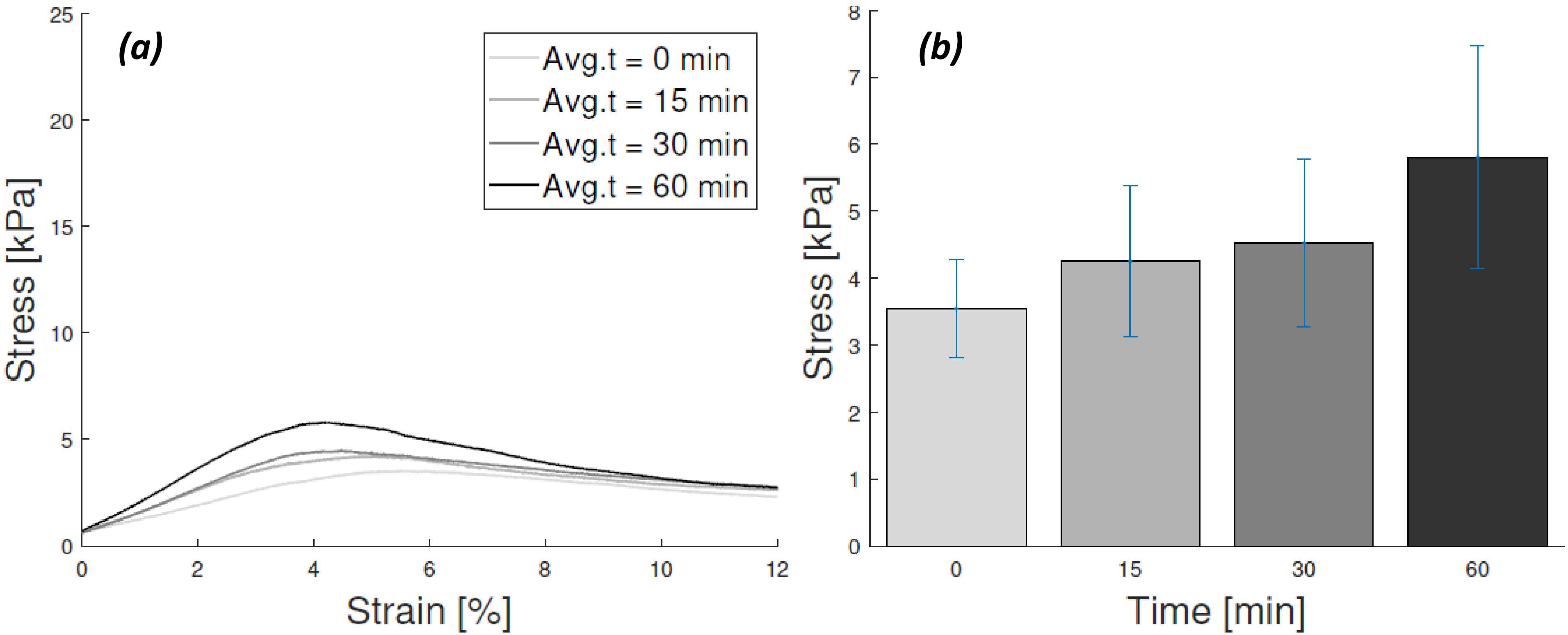


Effect of Membrane ***: SP0.00-NM-DR3.***

Average comparison: (a) stress-strain curves, (b) compressive strength and standard deviation

- Combination of 0.00% SP without membrane experienced a high reduction in strength and stiffness, even at very early ages

Compression tests

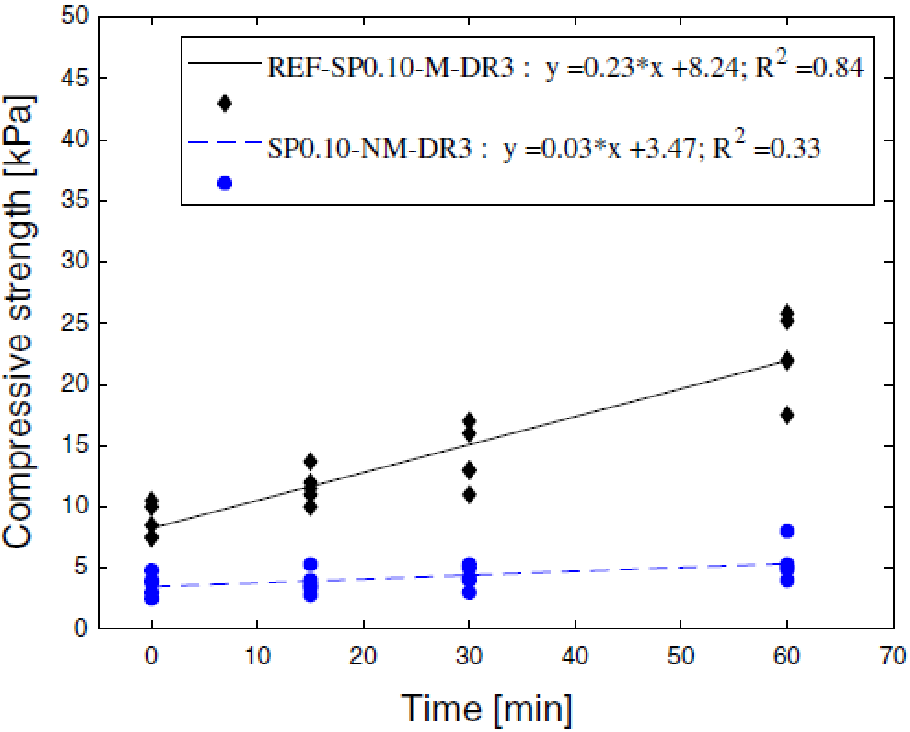


***Effect of Membrane*: SP0.10-NM-DR3.**

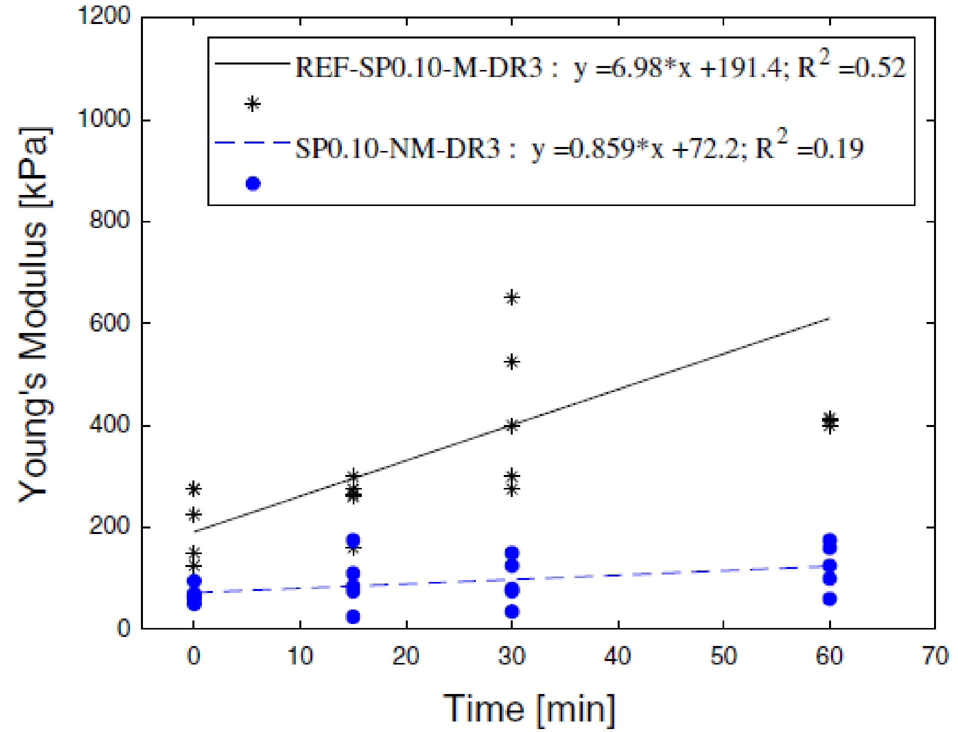
Average comparison: (a) stress-strain curves, (b) compressive strength and standard deviation

- Such effect was more evident for the mix with 0.10% SP, where the only source of disturbance was due to demoulding

Compression tests



(a)



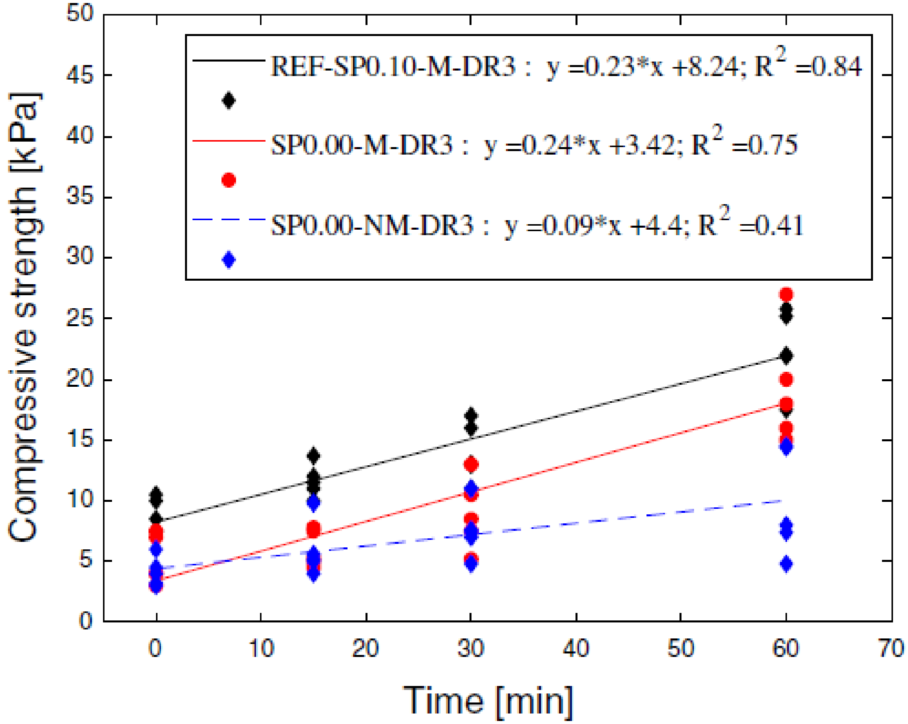
(b)

Effect of Membrane*: *SP0.10

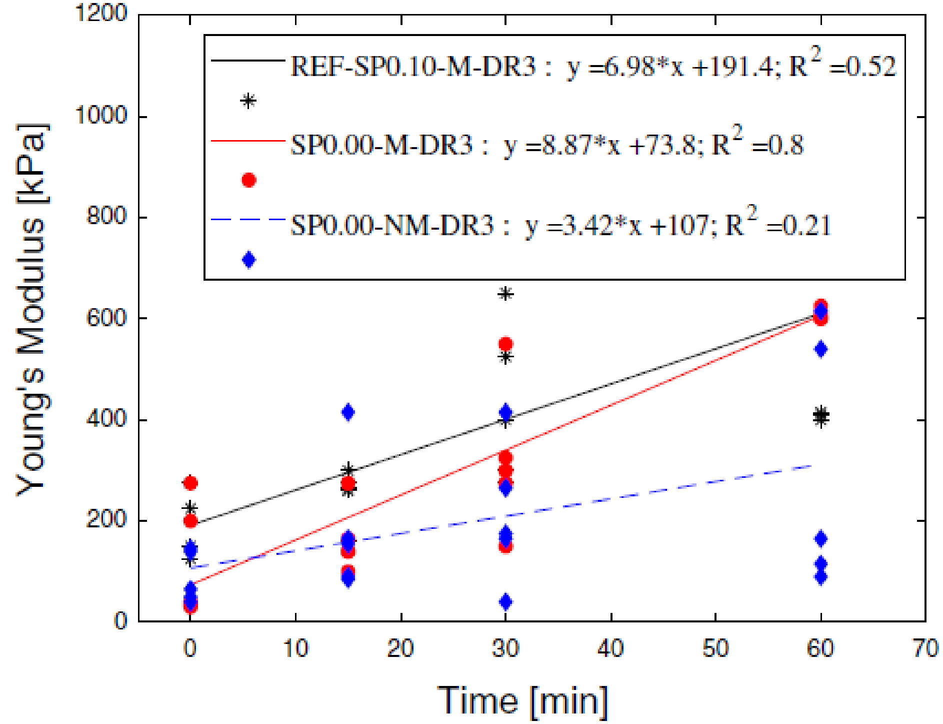
Evolution over time of the compressive strength (a) and Young's modulus (b).

- At t = 60 min, compressive strength decreased from 22.48 to 5.44 kPa (up to 75%)
- Elastic modulus decreased by approximately 80%

Compression tests



(a)



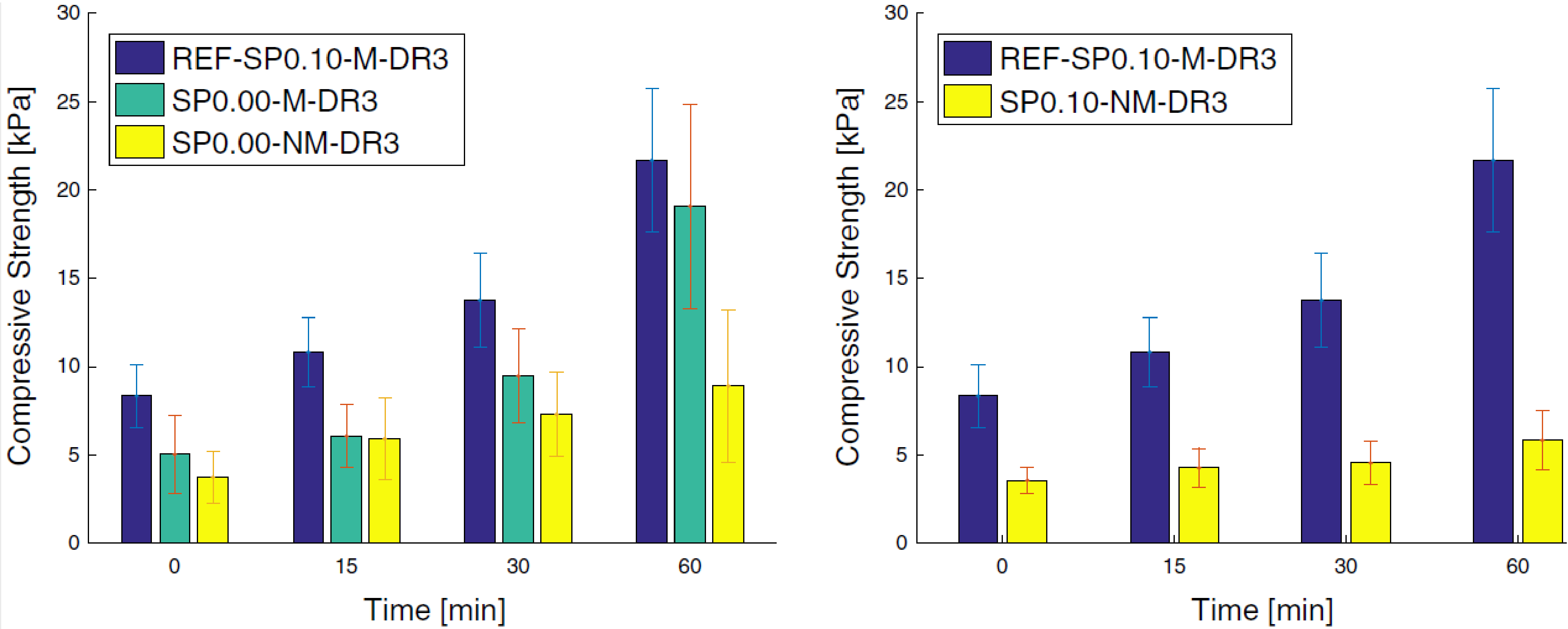
(b)

***Effect of Membrane*: SP0.00**

Evolution over time of the compressive strength (a) and Young's modulus (b).

- At t = 60 min, compressive strength decreased from 19.20 to 9.82 kPa (up to 50%)
- Elastic modulus decreased from 627 kPa to 305 kPa (approximately 50%)

Compression tests



Effect of Membrane

Average comparison: compressive strength and standard deviation

- Effect of membrane was more evident as the concrete age increases, especially for mix with 0.10% SP

Compression tests

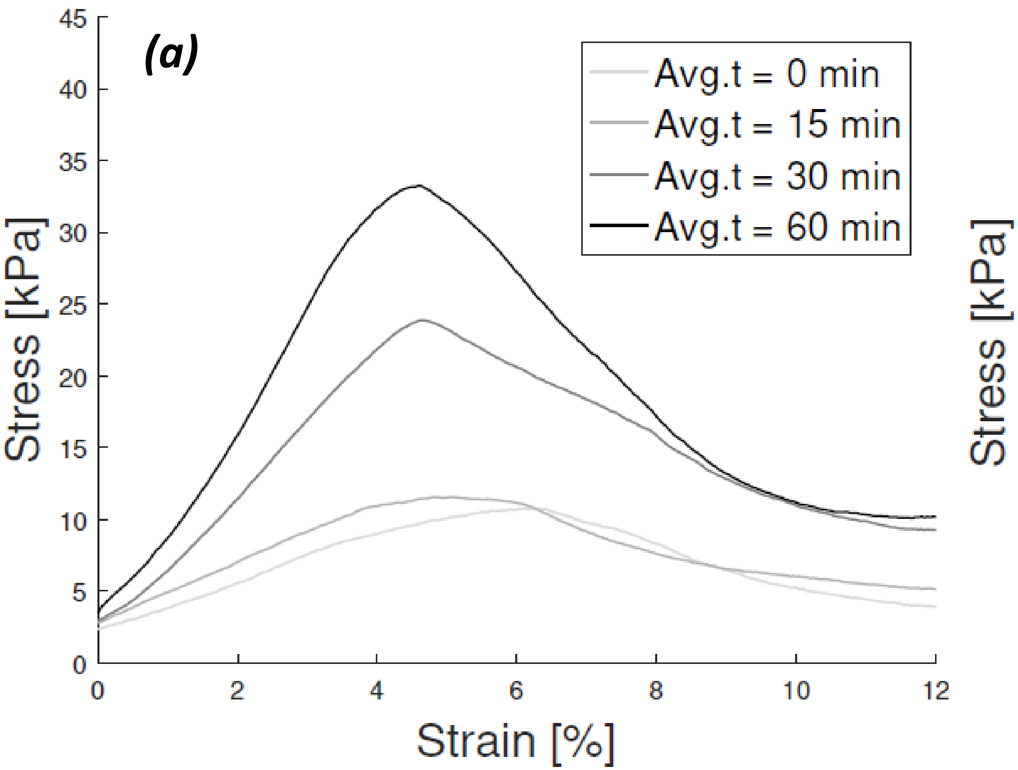
	Concrete Age			
	0 min	15 min	30 min	60 min
	Compressive Strength, σ			
REF-SP0.10-M-DR3	**8.80 kPa**	**11.64 kPa**	**14.00 kPa**	**22.48 kPa**
SP0.10-NM-DR3	3.62 kPa	3.82 kPa	4.30 kPa	5.44 kPa
SP0.00-M-DR3	5.10 kPa	6.02 kPa	8.94 kPa	19.20 kPa
SP0.00-NM-DR3	4.14 kPa	5.92 kPa	7.56 kPa	9.82 kPa
	RSD (σ)			
REF-SP0.10-M-DR3	**15.87 %**	**11.76 %**	**17.49 %**	**14.72 %**
SP0.10-NM-DR3	25.74 %	24.45 %	21.06 %	27.78 %
SP0.00-M-DR3	39.46 %	25.23 %	33.17 %	25.82 %
SP0.00-NM-DR3	29.08 %	37.97 %	29.42 %	44.75 %
	Young's Modulus, E			
REF-SP0.10-M-DR3	**210 kPa**	**252 kPa**	**430 kPa**	607 kPa
SP0.10-NM-DR3	68 kPa	94 kPa	93 kPa	124 kPa
SP0.00-M-DR3	116 kPa	164 kPa	320 kPa	**627 kPa**
SP0.00-NM-DR3	88 kPa	182 kPa	212 kPa	305 kPa
	RSD (E)			
REF-SP0.10-M-DR3	**33.25 %**	**21.31 %**	**36.63 %**	44.83 %
SP0.10-NM-DR3	25.72 %	58.32 %	48.48 %	37.33 %
SP0.00-M-DR3	98.36 %	40.41 %	45.35 %	**6.71 %**
SP0.00-NM-DR3	57.47 %	74.31 %	66.52 %	82.50 %

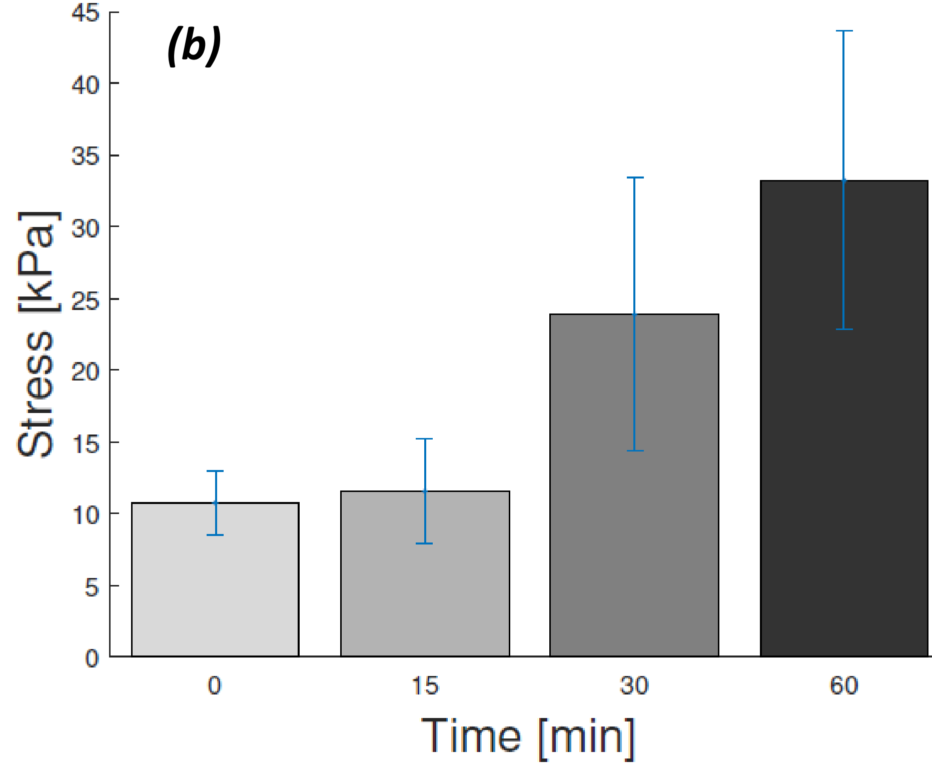
Effect of Membrane

Average comparison: Compressive strength, Young's modulus and relative standard deviation

- Results without membrane had higher relative standard deviation: at 60 min, these reached 44.75%

Compression tests



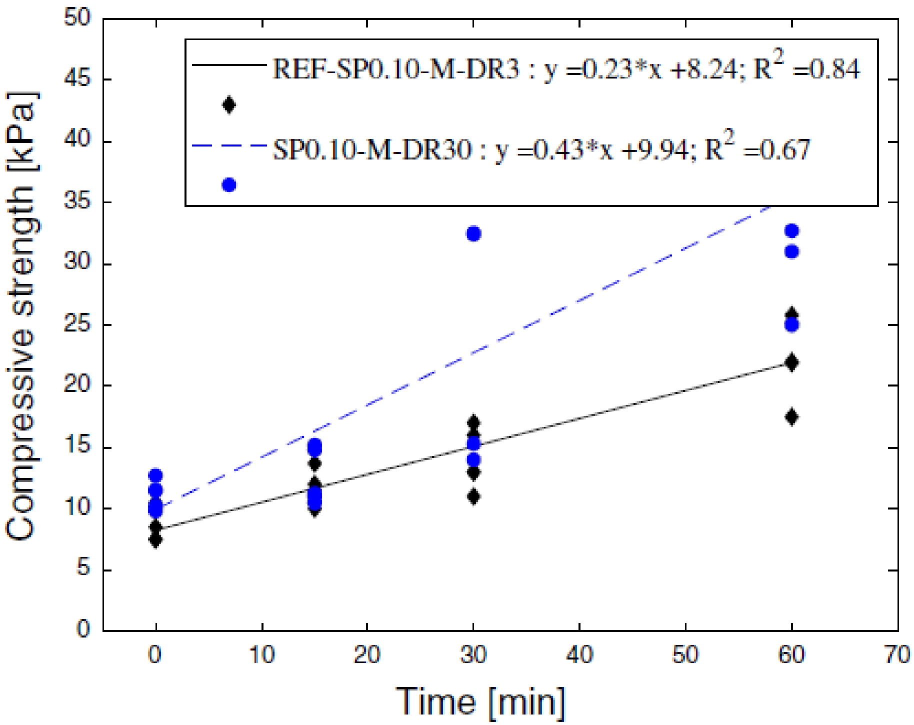


***Effect of Displacement Rate*: SP0.10-M-DR30.**

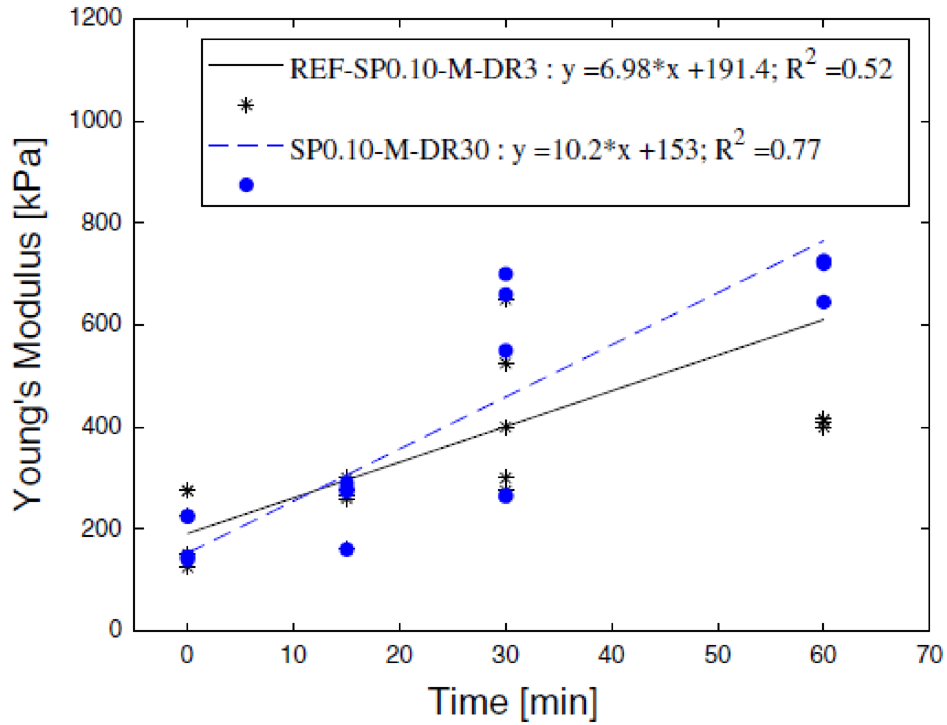
Average comparison: (a) stress-strain curves, (b) compressive strength and standard deviation

- Improvements on compressive strength when test was carried out at a higher displacement rate

Compression tests



(a)



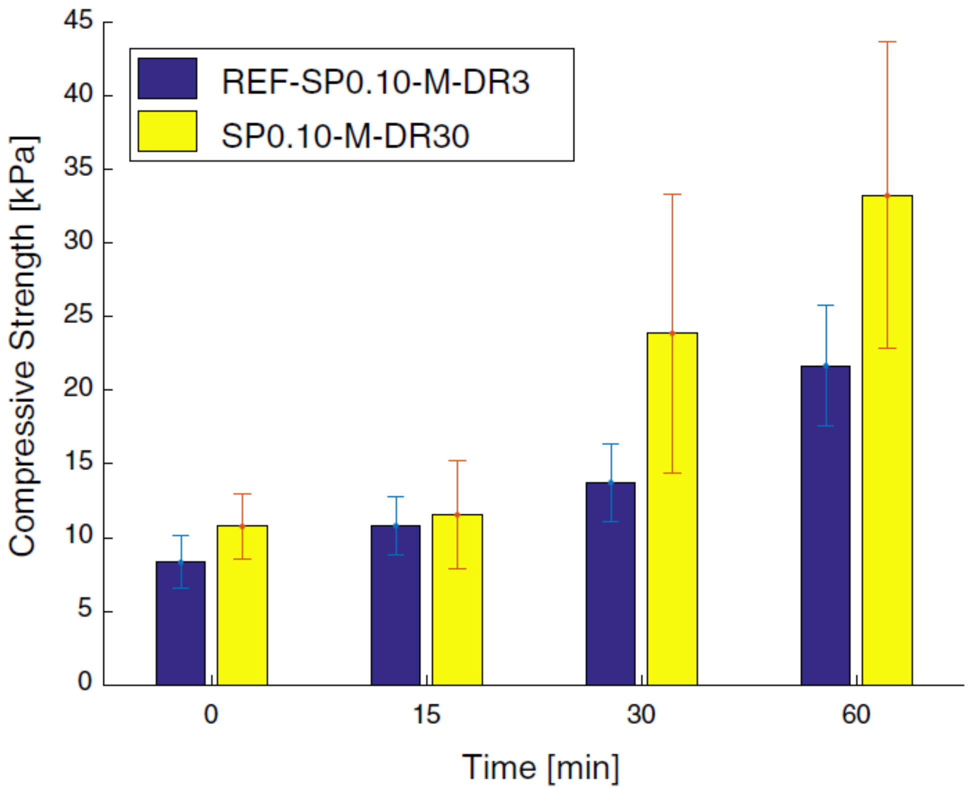
(b)

Effect of Displacement Rate

Evolution over time of the compressive strength (a) and Young's modulus (b).

- In general, displacement rate affected strength values rather than the stiffness.
- At low concrete ages (up to 15 min), the increase in strength was +20%

Compression tests



Effect of Displacement Rate

Average comparison: compressive strength and standard deviation

- At t = 60 min, the compressive strength increased from 22.48 kPa to 34.84 kPa, a percentage increase of about 55%

Compression tests

	Concrete Age			
	0 min	15 min	30 min	60 min
	Compressive Strength, σ			
REF-SP0.10-M-DR3	8.80 kPa	11.64 kPa	14.00 kPa	22.48 kPa
SP0.10-M-DR30	**11.14 kPa**	**12.54 kPa**	**26.04 kPa**	**34.84 kPa**
	RSD (σ)			
REF-SP0.10-M-DR3	15.87 %	**11.76 %**	**17.49 %**	**14.72 %**
SP0.10-M-DR30	**10.40 %**	18.06 %	40.35 %	22.30 %
	Young's Modulus, E			
REF-SP0.10-M-DR3	**210 kPa**	252 kPa	430 kPa	607 kPa
SP0.10-M-DR30	176 kPa	**256 kPa**	**488 kPa**	**763 kPa**
	RSD (E)			
REF-SP0.10-M-DR3	33.25 %	**21.31 %**	**36.63 %**	44.83 %
SP0.10-M-DR30	**25.44 %**	21.50 %	43.21 %	**17.93 %**

Effect of Displacement Rate

Average comparison: Compressive strength, Young's modulus and relative standard deviation

- With higher strain rate the experimental data were less reliable: results of DR30 had higher relative standard deviation (up to 40%)

3D@UniPV
Virtual Modeling and Additive Manufacturing for Advanced Materials

Objectives

UNIVERSITÀ DI PAVIA

GOAL

Demonstrate need in a ***standard procedure*** for 3D printable concrete mix: experimental results compared by varying testing procedures, investigating the effect of such variations on mechanical properties

STEPS

1. design a 3D printable concrete mix
2. define the testing programme
3. develop a standard procedure for uniaxial unconfined compression test
4. provide an analytical failure predictive model
5. define a standard method for creep test
6. provide a standard procedure for rheological test

Analytical failure model

Concrete material in early-age state has low strength and stiffness

Stability checks of have to be performed (as a function of increasing element height and building rate)

Stability checks include:

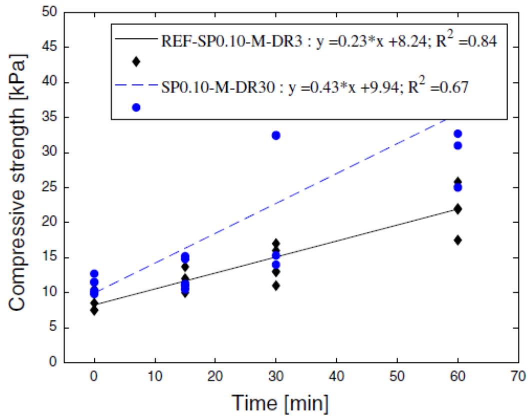
- **A compressive plastic yielding check**
- **A self-buckling instability check**

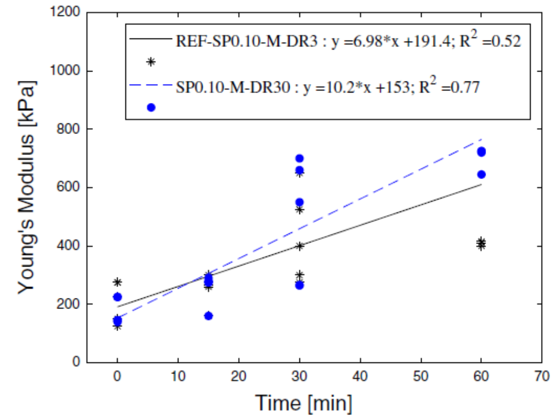
Element stability depends on temporal evolution of the mechanical parameters, derived from experimental testing

Analytical failure model

Continuous time-variation compressive strength **σc,max(t)** and stiffness **E(t)** laws obtained through linear regression of experimental data

σc,max(t)





E(t)

Compressive plastic yielding check

Self-buckling instability check

Compressive plastic yielding:

$$\sigma_v(t) = H(t)\rho g \geqslant \sigma_{c,max}(t)$$

Self-Buckling failure:

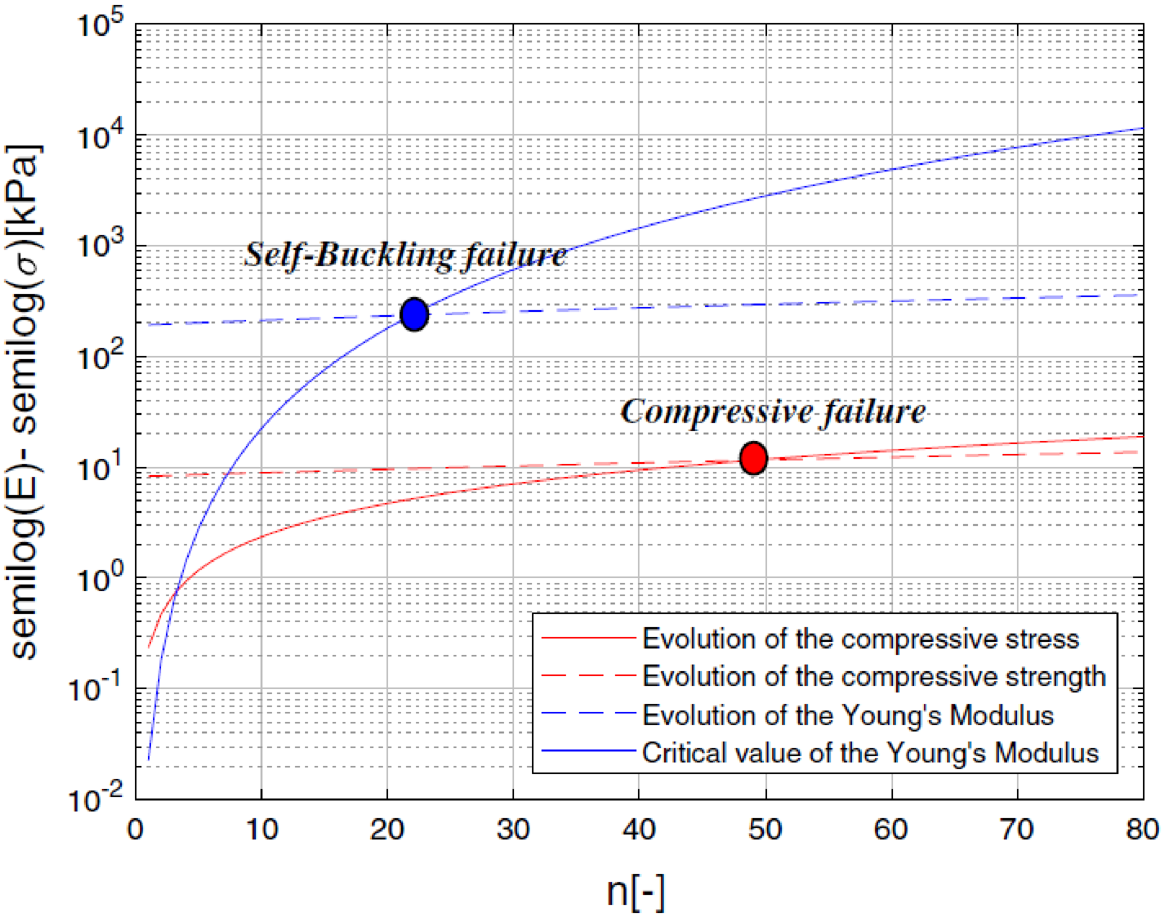
$$E(t) \leqslant E_{crit}(t) \approx 0.65^{-1}\frac{H^3(t)\rho g}{\delta^2}$$

Experimental data

Vertical stress in the first layer

Derived from the Greenhill's equation

Analytical failure model

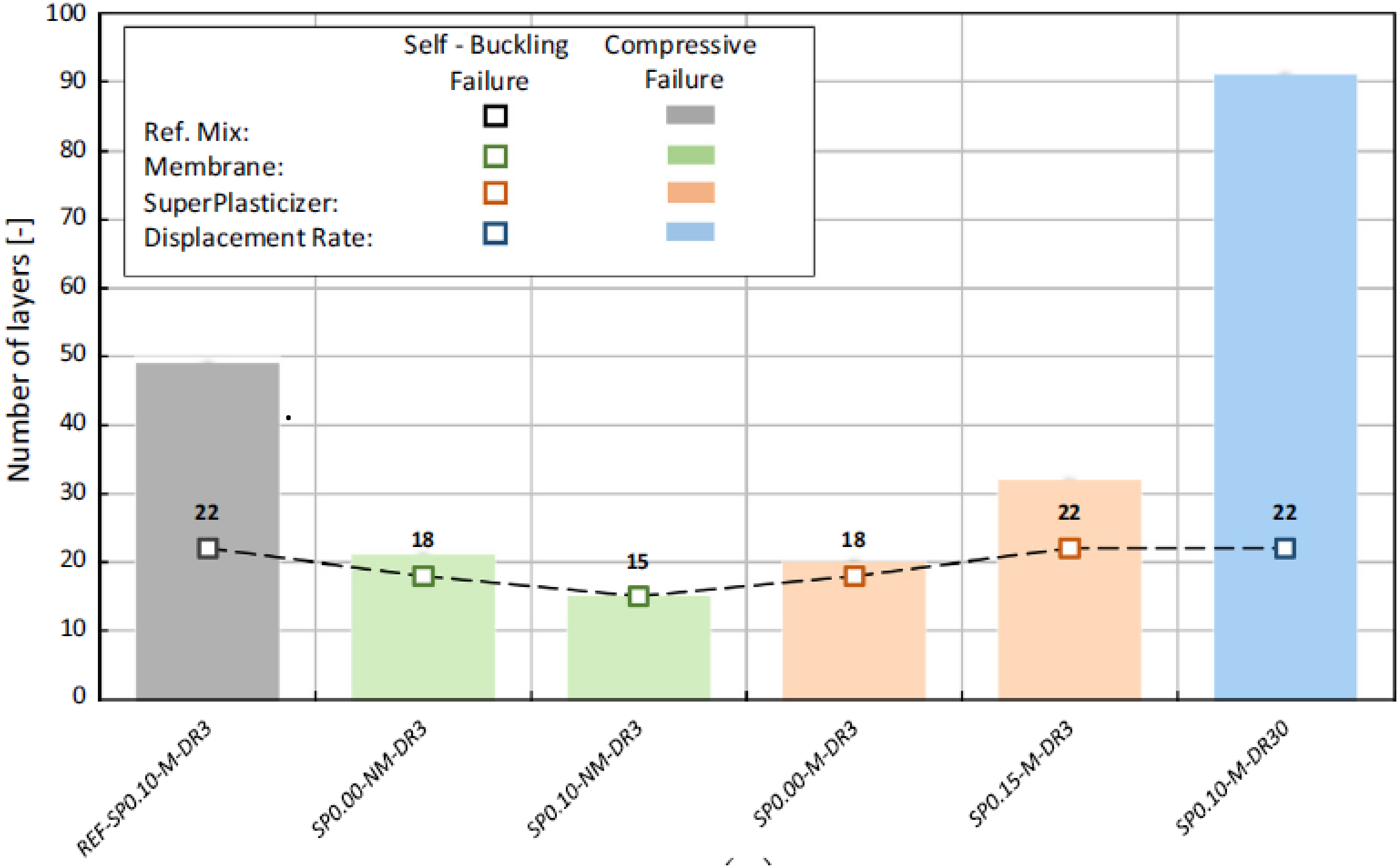


$$n = \frac{tB_R}{h_{layer}}$$

Comparison between the compressive strength and the vertical stress (red curves), between the Young's modulus and the critical elastic modulus (blue curves) for Reference Test.

- For reference test, maximum compressive strength achieved after 49 layers
- Self-buckling failure occurred after 22 layers

Analytical failure model



Summary of analytical failure prediction 'maximum layers' number – for each case examined

- Same numerical evaluation was made for each testing-condition, in all cases failure was due to the self-buckling (lower bound 15 layers)

Objectives

GOAL

Demonstrate need in a ***standard procedure*** for 3D printable concrete mix: experimental results compared by varying testing procedures, investigating the effect of such variations on mechanical properties

STEPS

1. design a 3D printable concrete mix
2. define the testing programme
3. develop a standard procedure for uniaxial unconfined compression test
4. provide an analytical failure predictive model
5. define a standard method for creep test
6. provide a standard procedure for rheological test

Creep testing

3D printable concrete is characterized by:

- high cement paste volume
- low water-to-cement ratio (w/c)
- high dosage of mineral additions and superplasticizer

High paste volumes are more sensitive to creep and shrinkage. Higher creep strains are experienced if concrete is demoulded and loaded at ages inferior to 1 day [5,6]

As the height of the printed element increases, so does the layer compression under self-weight (hydrostatic pressure).

CREEP TESTS

[5] NIYOGI, A. K.; HSU, P.; MEYERS, B. L. The influence of age at time of loading on basic and drying creep. Cement and Concrete Research, 1973, 3.5: 633-644.

[6] ØSTERGAARD, Lennart, et al. Tensile basic creep of early-age concrete under constant load. Cement and concrete research, 2001, 31.12: 1895-1899.

Creep testing

We performed a sensitivity analysis considering:

- ***Evolution over time***: strength and stiffness of early-age concrete changes during the printing process
- ***Materials and sample preparation***: during 3D printing process, it is possible to experience variations in the workability of the material
- ***Compressive test set-up***: 3D printable concrete behaves as a visco-plastic Bingham material, response is affected by testing time/loading rate

VARIATIONS

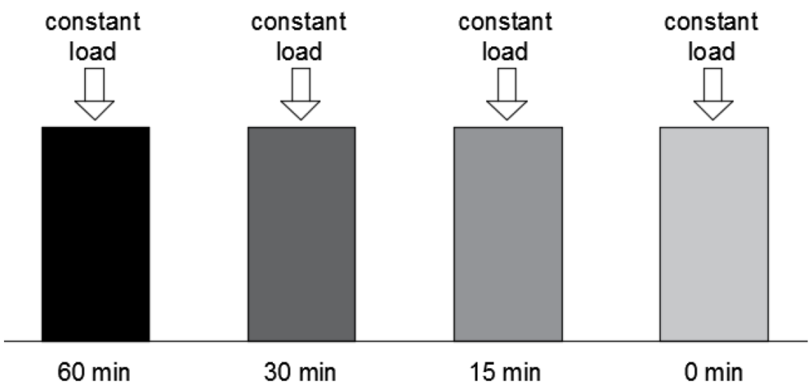
1. Creep Tests at distinct **CONCRETE AGES**
   t = 0, 15, 30 and 60 min
2. Creep Tests at distinct **SUPERPLASTICIZER AMOUNT**
   SP = 0.0, 0.1, 0.15%
3. Creep Tests at distinct **DISPLACEMENT RATE**
   Dr = 3mm/min vs 30mm/min
4. **TESTING TIME**
   T = 300 s vs 900 s

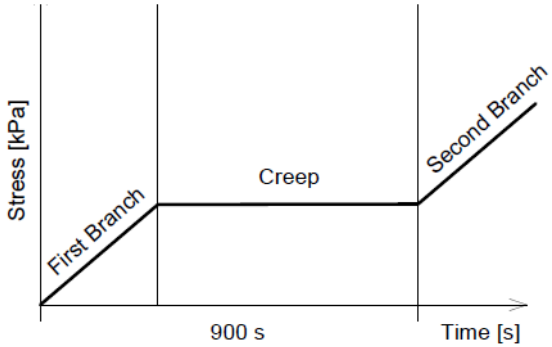
Creep testing

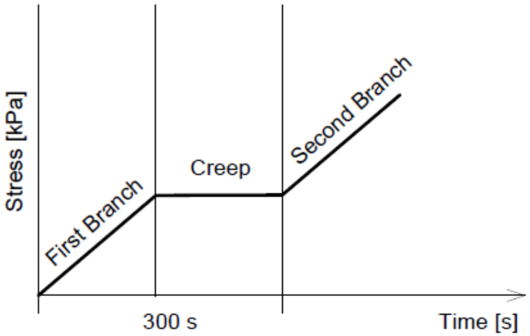
Test protocol

- Displacement-control condition (up to 8N)
- Room temperature T = 22°C
- Controlled relative humidity RH = 60%
- 900 and 300 s (long- and short-term creep)

8N, self-weight of the specimen





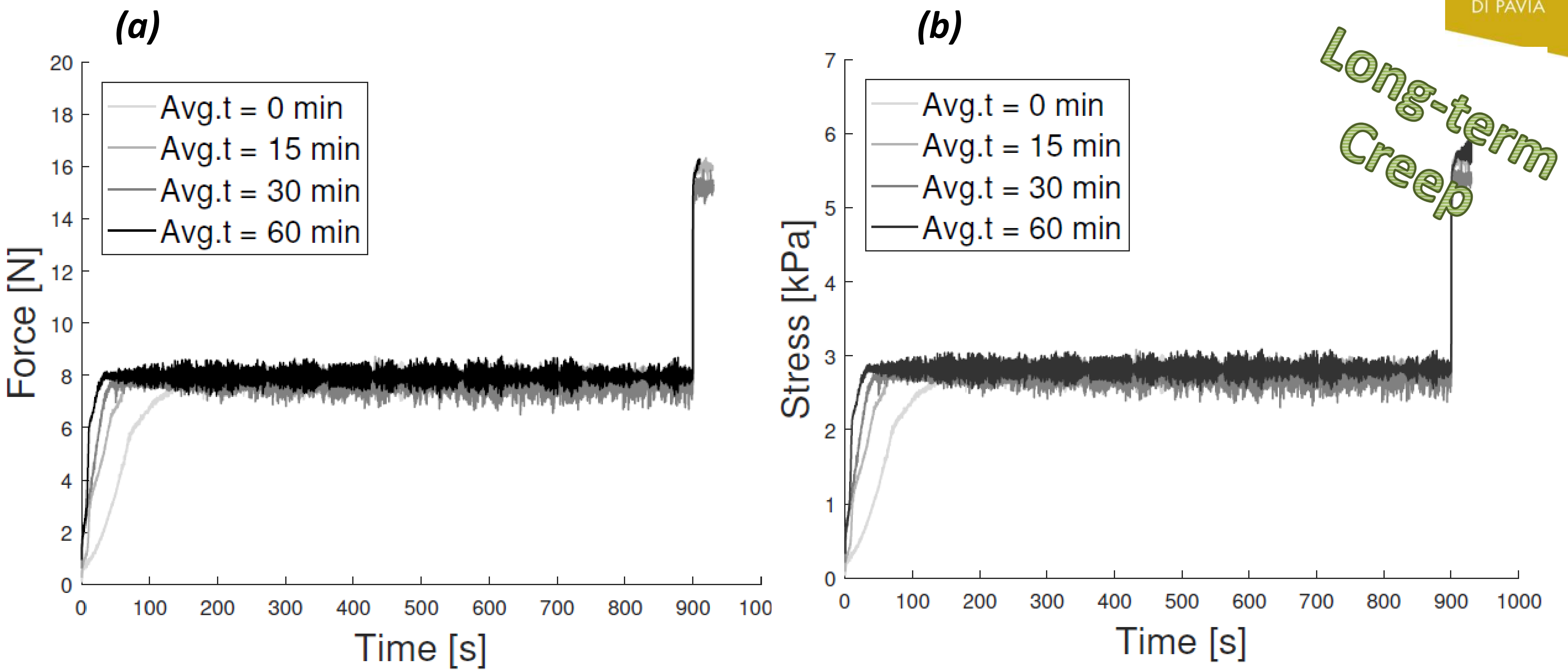


Variables	Creep tests				
Acronym	REF-SP0.10-LC-DR3	SP0.10-LC-DR30	SP0.10-SC-DR3	SP0.00-SC-DR3	SP0.15-SC-DR3
1. Age [min]	0, 15, 30, 60	0, 15, 30, 60	0, 15, 30, 60	0, 15, 30, 60	0, 15, 30, 60
2. Superplasticizer [%]	0.10	0.10	0.10	0.00	0.15
3. Testing Time [sec]	900	900	300	300	300
4. Displacement rate [mm/min]	3.0	30.0	3.0	3.0	3.0
Samples per set	5	5	5	5	5
Tot. samples	20	20	20	20	20

reference test
REF-SP0.10-LC-DR3

Test matrix.

Creep testing



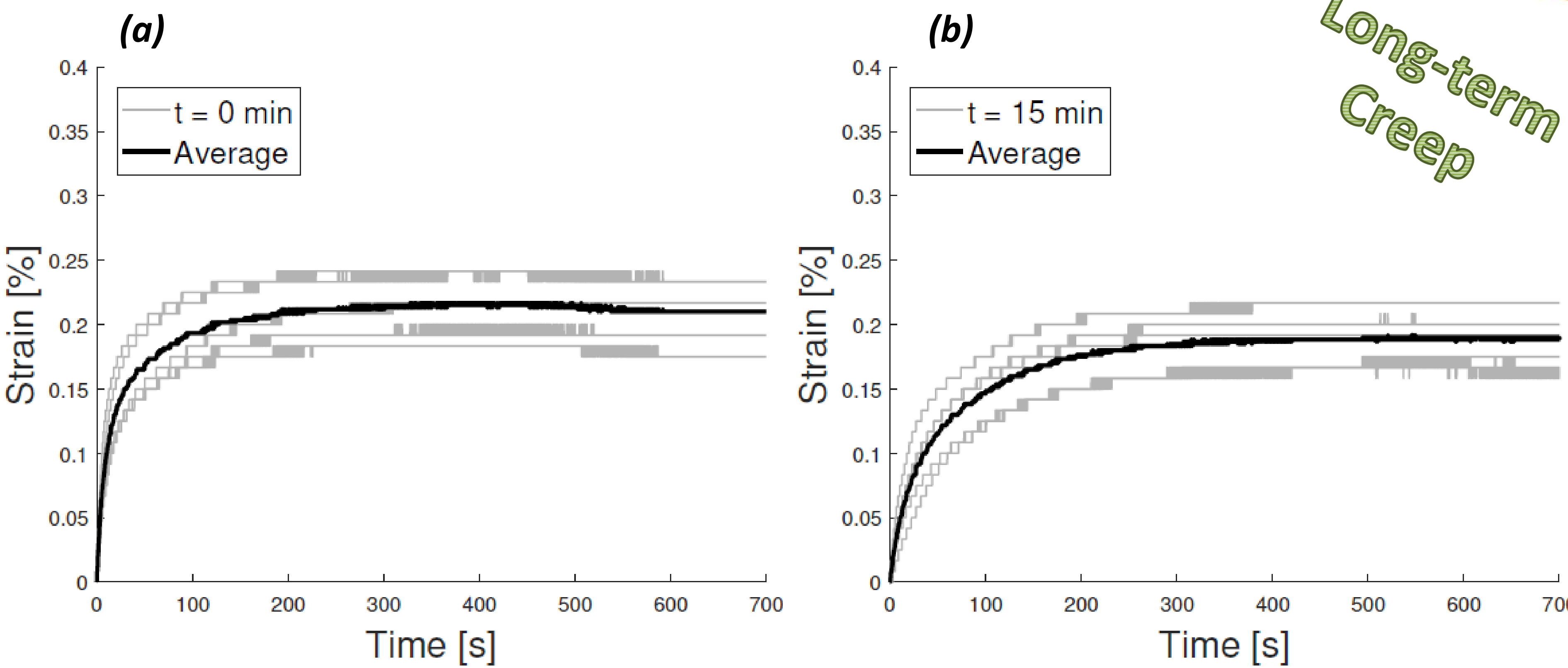
Load Application – Long term creep

Average comparison: (a) force-displacement curves and (b) stress-strain curves

- Time due to reach constant self weight applied (8N - 2.8kPa) increases as the sample stiffness decreases

Creep testing

Long-term Creep

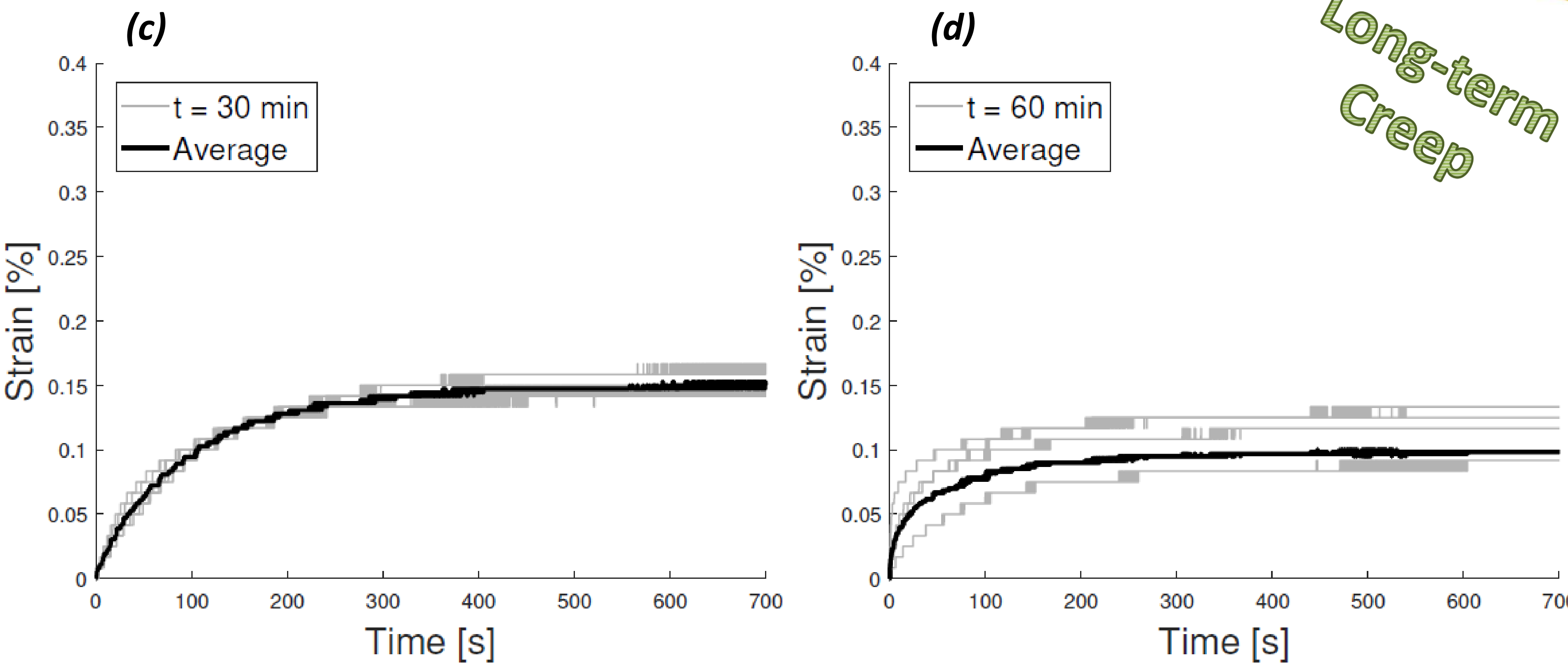


***Effect of Age*: REF-SP0.10-LC-DR3.**
Average and individual results at different times: (a) 0 min, (b) 15 min.

- Creep curves are extrapolated from total strain curves, removing instantaneous strain

Creep testing

Long-term Creep

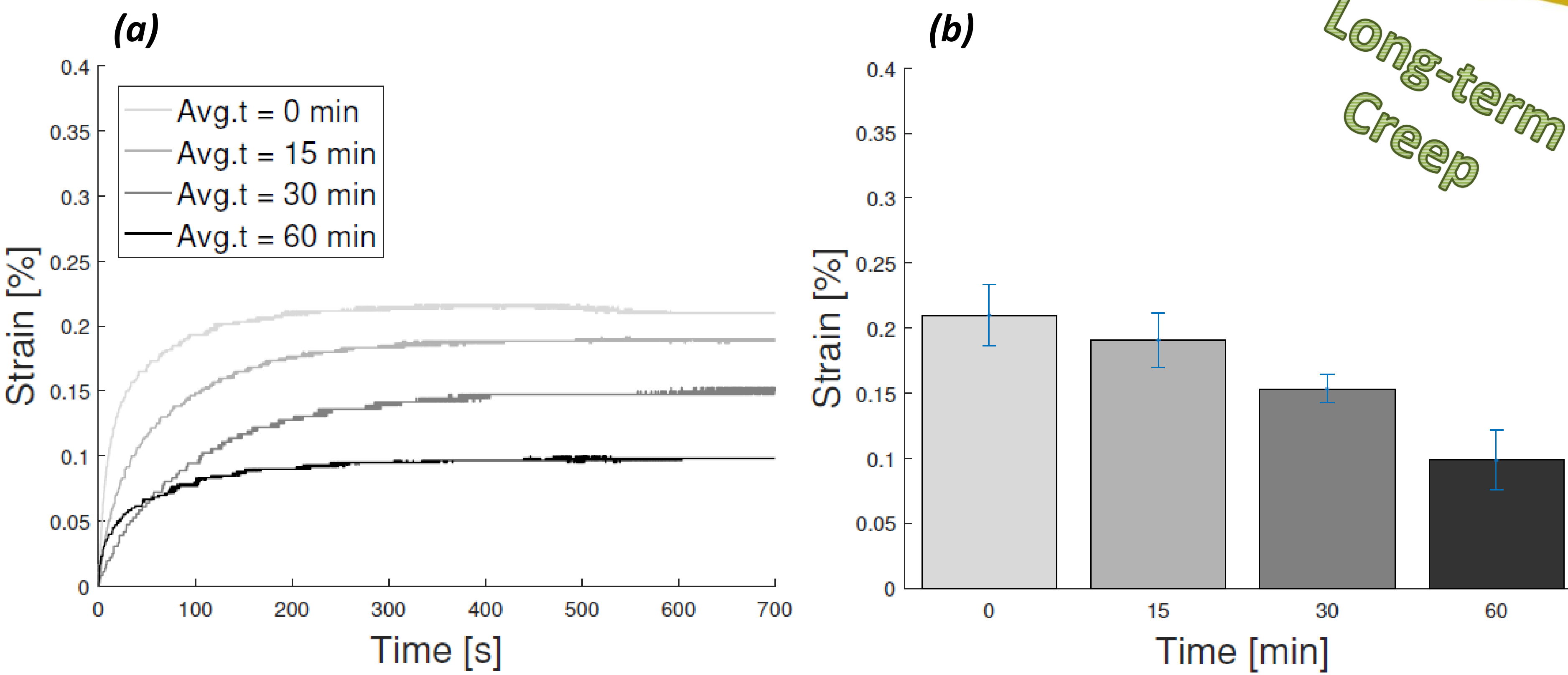


***Effect of Age*: REF-SP0.10-LC-DR3.**
Average and individual results at different times: (c) 30 min, (d) 60 min.

- Average creep values stabilize after approximately 200 seconds, reaching a plateau

Creep testing

Long-term Creep



***Effect of Age*: REF-SP0.10-LC-DR3.**

Average comparison: (a) strain curves, (b) strain and standard deviation

- Creep strain decreases as the concrete harden, starting with 0.21% (t = 0 minutes) and halving in one hour

Creep testing

Long-term Creep

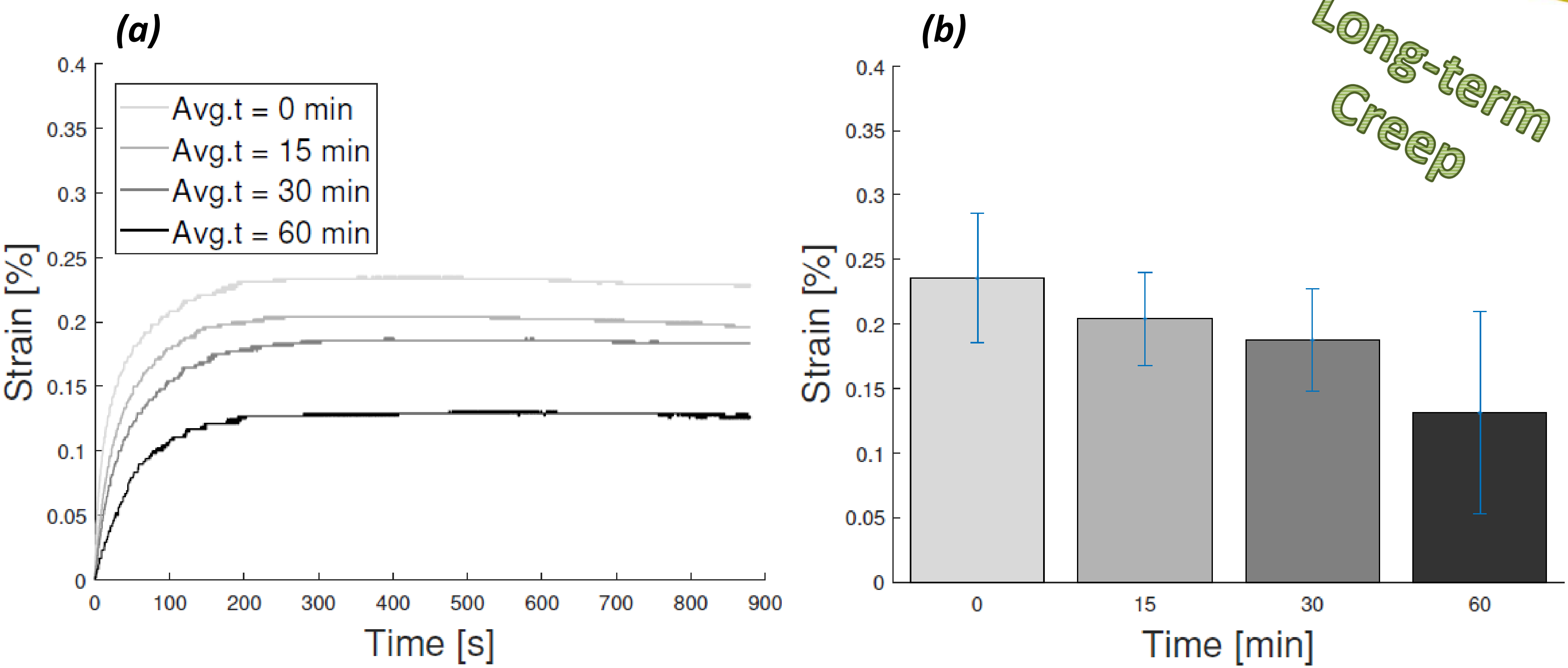
	Curing Time			
	0 min peak averages	**15 min** peak averages	**30 min** peak averages	**60 min** peak averages
Creep Strain [%]	0.21	0.19	0.15	0.10
Strain Standard Deviation [%]	0.0232	0.0178	0.0103	0.0252
Relative Strain Standard Deviation [%]	11.05	9.37	6.87	25.21
Tot. number of samples	**5**	**5**	**5**	**5**

***Effect of Age*: REF-SP0.10-LC-DR3.**
Average comparison: Creep strain, standard deviation and relative standard deviation

- Creep progressively decreases from a peak of 0.21%, with an increasing relative standard deviation (up to 25%).

Creep testing

Long-term Creep



***Effect of Displacement Rate*: SP0.10-LC-DR30.**
Average comparison: (a) strain curves, (b) strain and standard deviation

- Increasing the displacement rate, creep remains approximately unvaried (0.23%), with an increased relative standard deviation (up to 47%).

Creep testing

Long-term Creep

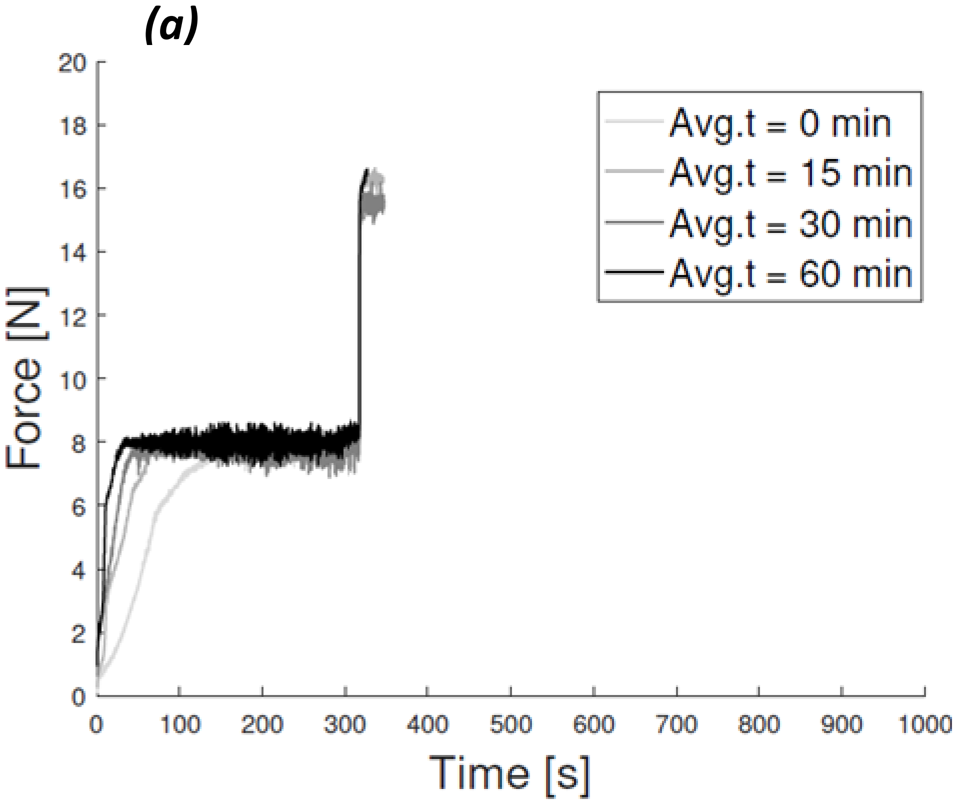
	Curing Time			
	0 min peak averages	15 min peak averages	30 min peak averages	60 min peak averages
Creep Strain [%]	0.23	0.21	0.20	0.13
Strain Standard Deviation [%]	0.0382	0.0291	0.0283	0.0612
Relative Strain Standard Deviation [%]	16.61	13.86	14.15	47.08
Tot. number of samples	5	5	5	5

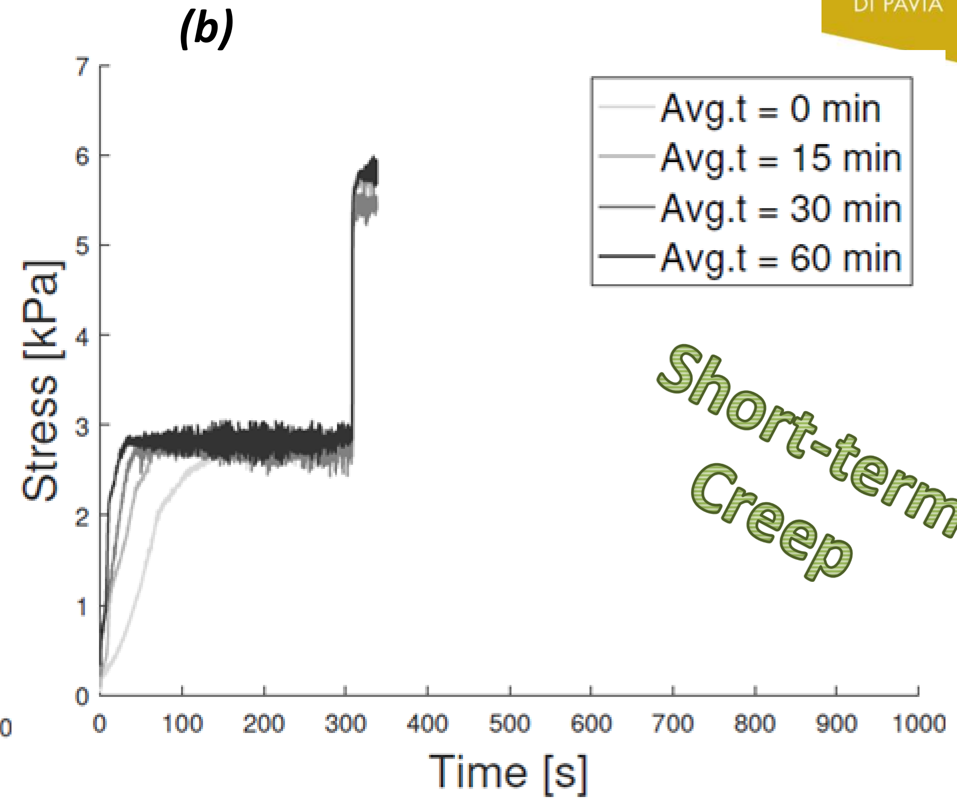
***Effect of Age*: REF-SP0.10-LC-DR30.**

Average comparison: Creep strain, standard deviation and relative standard deviation

- Increasing the displacement rate, creep remains approximately unvaried (0.23%), with an increased relative standard deviation (up to 47%).

Creep testing





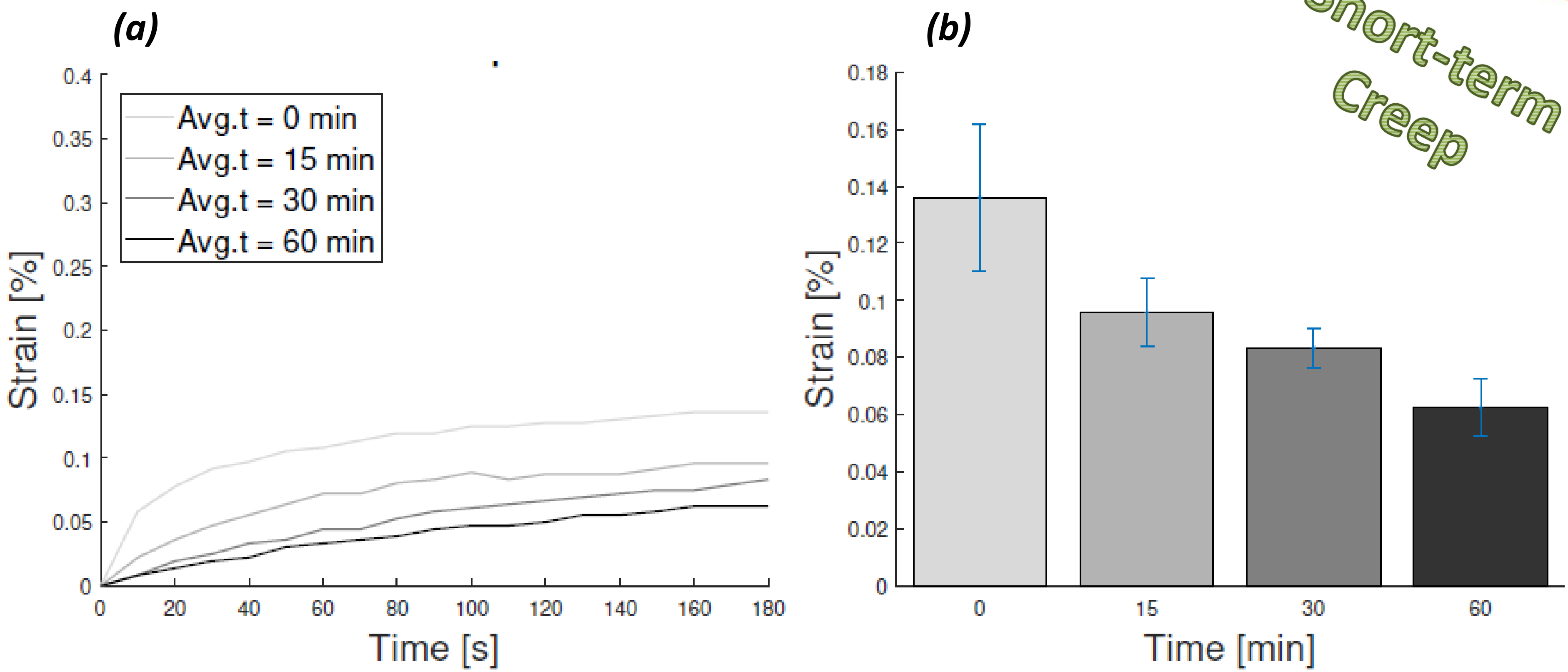
Load Application – Short term creep

Average comparison: load application, (a) force-time curves and (b) stress-time curves

- Time due to reach constant self weight applied (8N - 2.8kPa) increases as the sample stiffness decreases

Creep testing

Short-term Creep



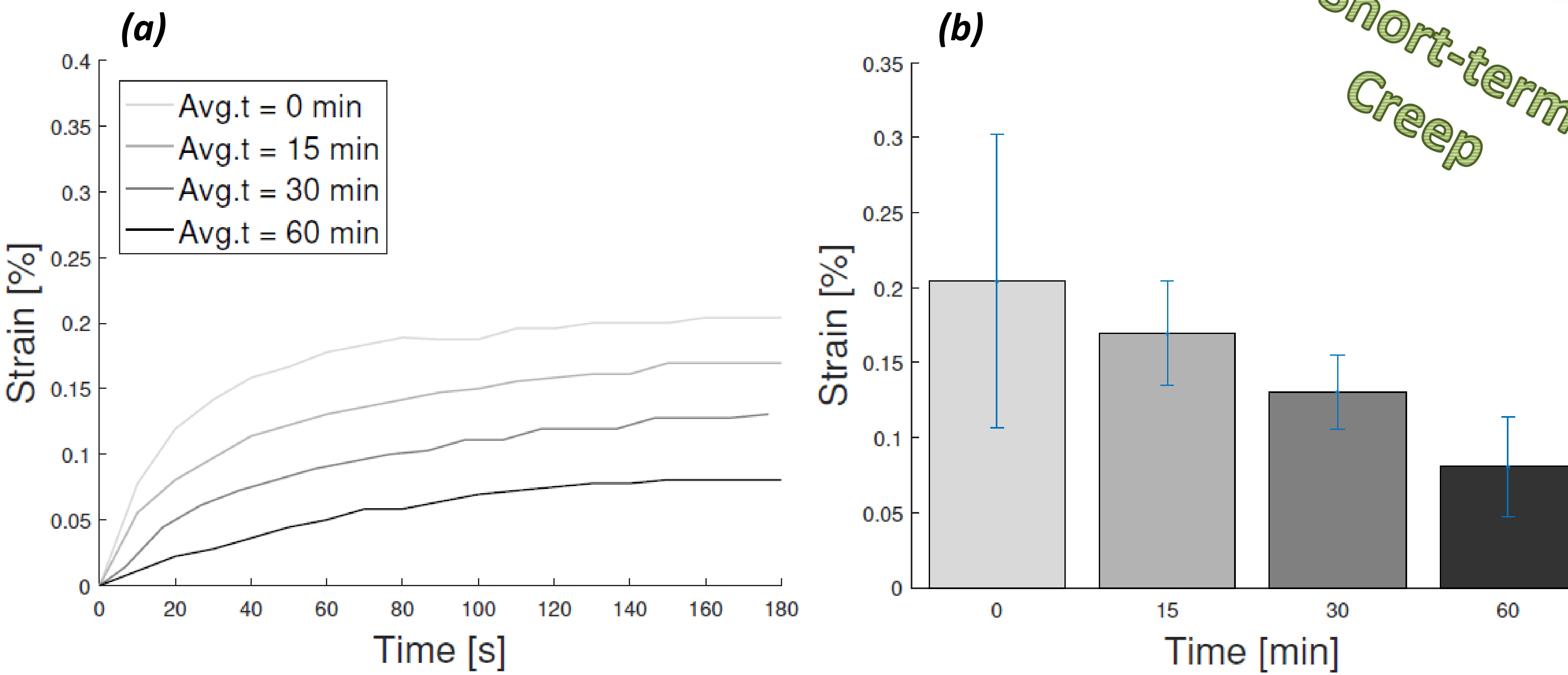
***Effect of SuperPlasticizer* : SP0.00-SC-DR3.**

Average comparison: (a) strain curves, (b) strain and standard deviation

- Creep increases as the amount of SP increases, starting from a peak of 0.136% (relative standard deviation 19%) for 0.00% of SP

Creep testing

Short-term Creep

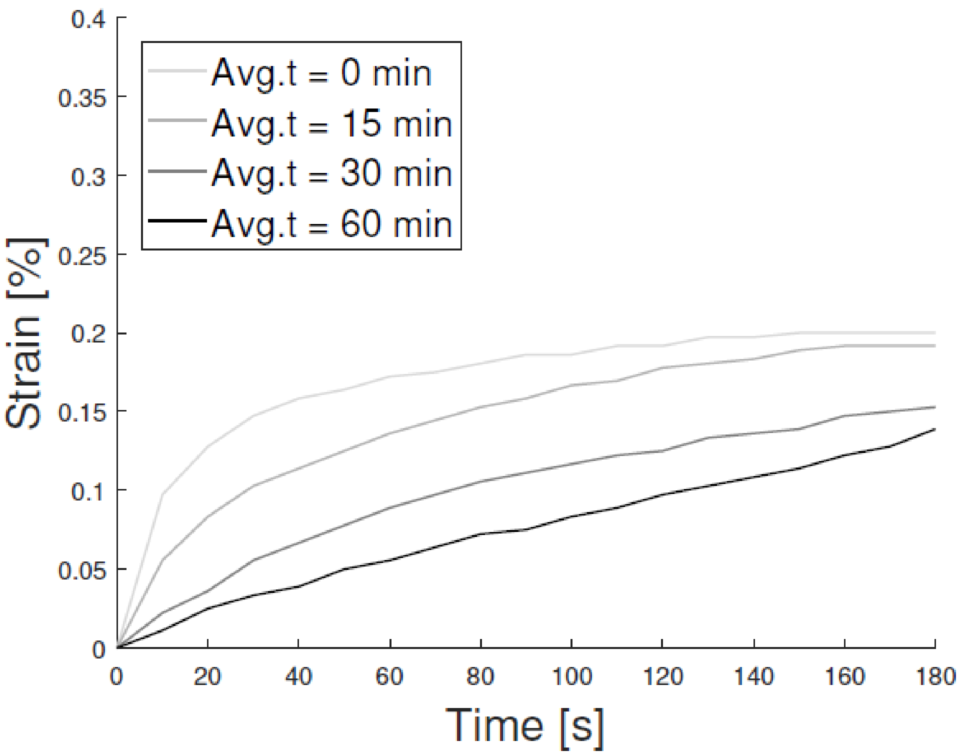


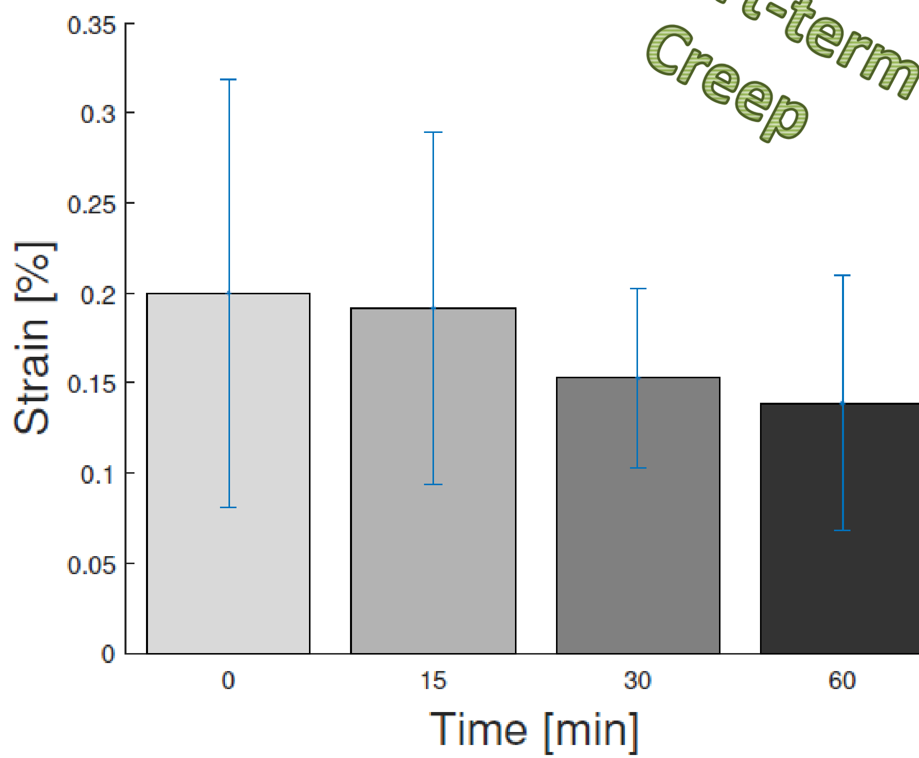
***Effect of SuperPlasticizer* : SP0.10-SC-DR3.**
Average comparison: (a) strain curves, (b) strain and standard deviation

- Creep increases as the amount of SP increases, starting from a peak of 0.200% (relative standard deviation 48%) for 0.10% of SP

Creep testing

Short-term Creep





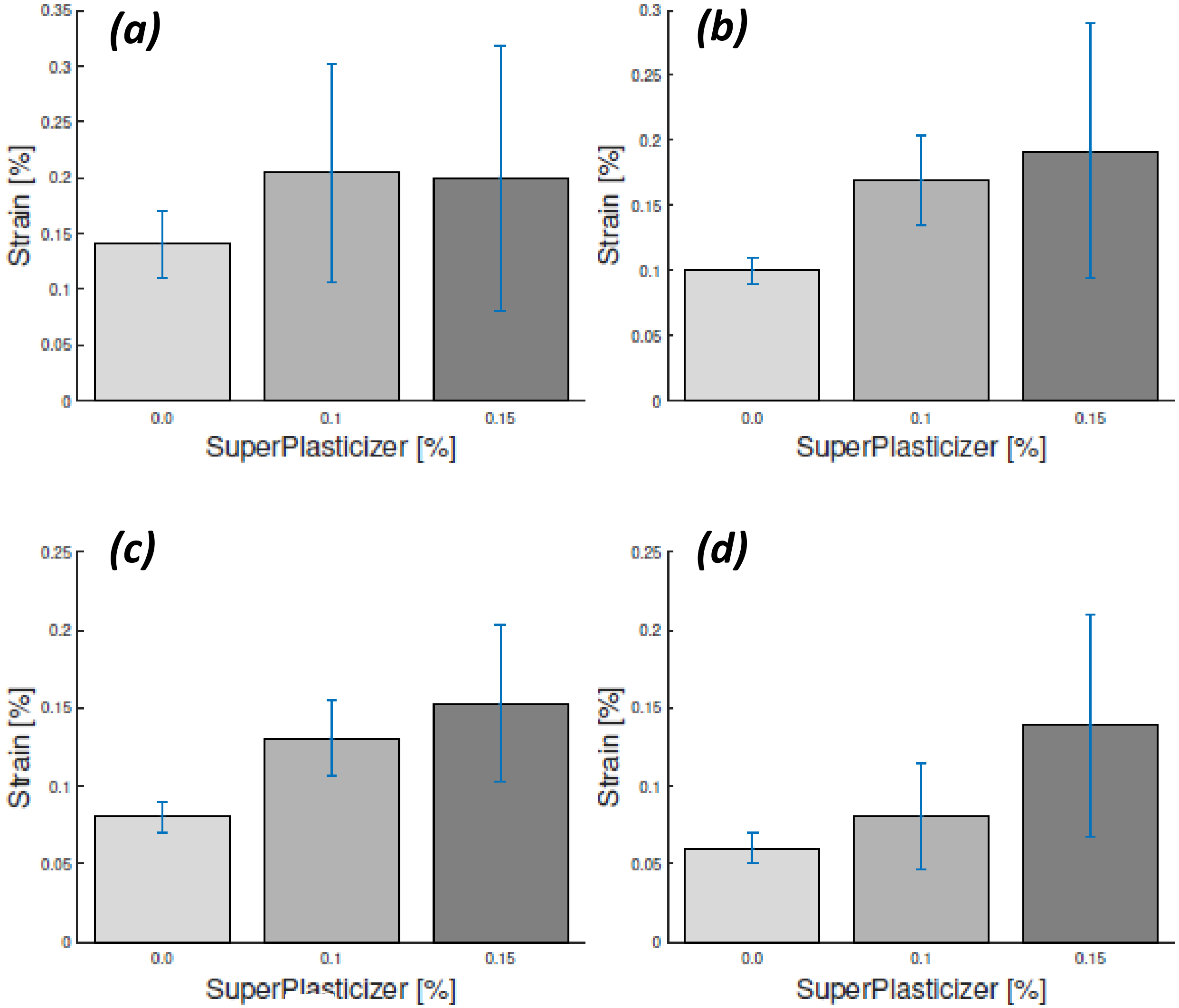
Effect of SuperPlasticizer ***: SP0.15-SC-DR3.***

Average comparison: (a) strain curves, (b) strain and standard deviation

- Creep increases as the amount of SP increases, starting from a peak of 0.204% (relative standard deviation 59%) for 0.15% of SP

Creep testing

Short-term Creep



Effect of SuperPlasticizer

Average comparison: (a) 0 minutes, (b) 15 minutes, (c) 30 minutes, (d) 60 minutes

Creep testing

Short-term Creep

Effect of SuperPlasticizer

	Curing Time			
	0 min peak averages	15 min peak averages	30 min peak averages	60 min peak averages
SP0.00-SC-DR3	0.136 [%]	0.096 [%]	0.083 [%]	0.063 [%]
SP0.10-SC-DR3	0.200 [%]	0.169 [%]	0.131 [%]	0.081 [%]
SP0.15-SC-DR3	0.204 [%]	0.192 [%]	0.153 [%]	0.139 [%]
Tot. number of samples	15	15	15	15

Average comparison: Creep strain

	Curing Time			
	0 min peak averages	15 min peak averages	30 min peak averages	60 min peak averages
SP0.00-SC-DR3	19.12 [%]	12.50 [%]	8.43 [%]	15.87 [%]
SP0.10-SC-DR3	48.04 [%]	20.12 [%]	18.32 [%]	40.74 [%]
SP0.15-SC-DR3	59.5 [%]	51.04 [%]	31.37 [%]	51.08 [%]
Tot. number of samples	15	15	15	15

Average comparison: Relative standard deviation

- Creep strain decreases as concrete harden and increases as the superplasticizer increases. Superplasticizer affects test accuracy, that decreases for higher amounts

Objectives

GOAL

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STEPS

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3. develop a standard procedure for uniaxial unconfined compression test
4. provide an analytical failure predictive model
5. define a standard method for creep test
6. provide a standard procedure for rheological test

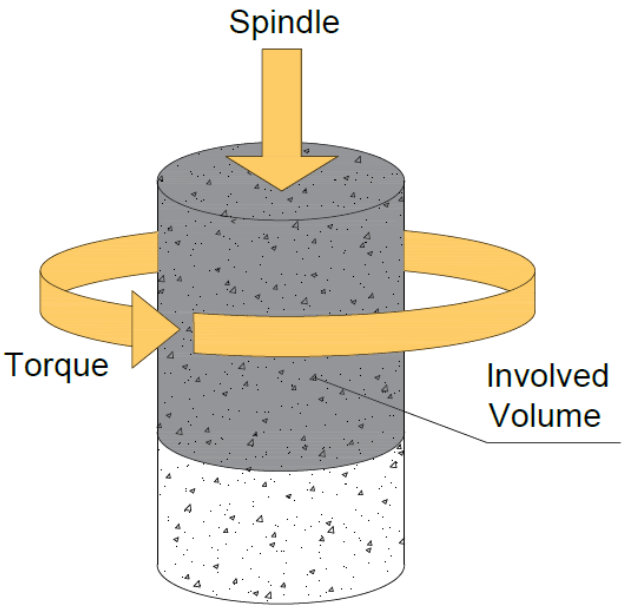
Rheological testing

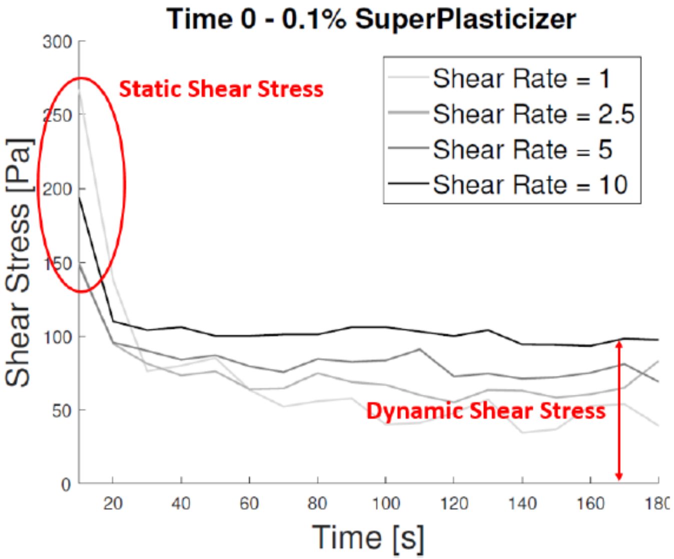
A cylindrical rheometer is used to determine the **plastic viscosity** and the **yield stress,** by imposing the shear rate and measuring the torque

Plastic viscosity: amount of increased shear stress when the shear rate increases

Static yield stress: maximum shear stress required to flow from the rest condition

Dynamic yield stress: minimum shear stress required to maintain the flow





Rheological testing

We performed a sensitivity analysis considering:

- ***Evolution over time*** : plastic viscosity and yield stress of early-age concrete changes during the printing process
- ***Materials and sample preparation***: during 3D printing process, it is possible to experience variations in the workability of the material
- ***Compressive test set-up***: 3D printable concrete behaves as a visco-plastic Bingham material, response is affected by testing protocol

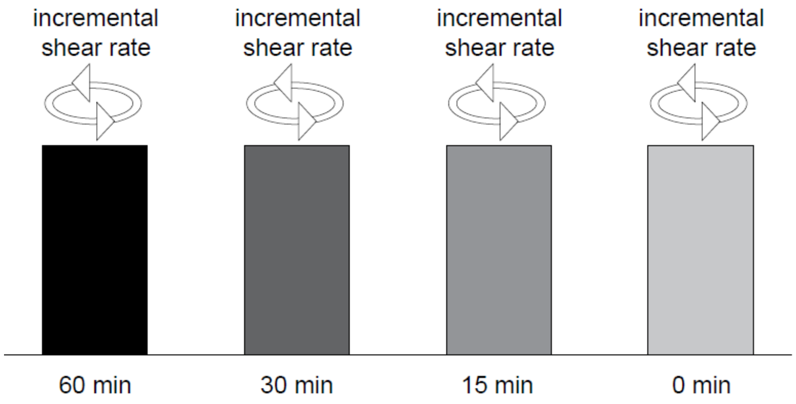
VARIATIONS

1. Rheological Tests at distinct **CONCRETE AGES**
   t = 0, 15, 30 and 60 min
2. Rheological Tests at distinct **SUPERPLASTICIZER AMOUNT**
   SP = 0.1, 0.15%
3. Rheological Tests at distinct **SHEAR RATE**
   Up to Sr = 30 1/s

Rheological testing

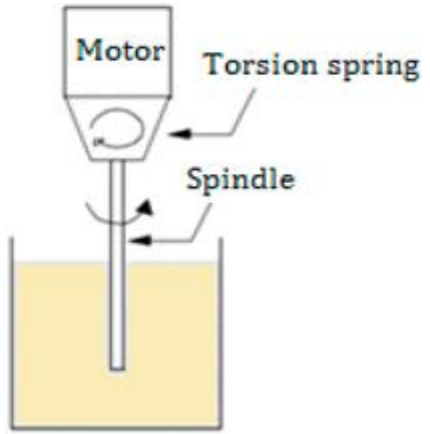
Test protocol

- The probe is a spindle (diameter 12 mm) that measures the torque
- Room temperature T = 22°C
- Controlled relative humidity RH = 60%
- A plastic 3D-printed container is used
- Duration of the test 180 sec

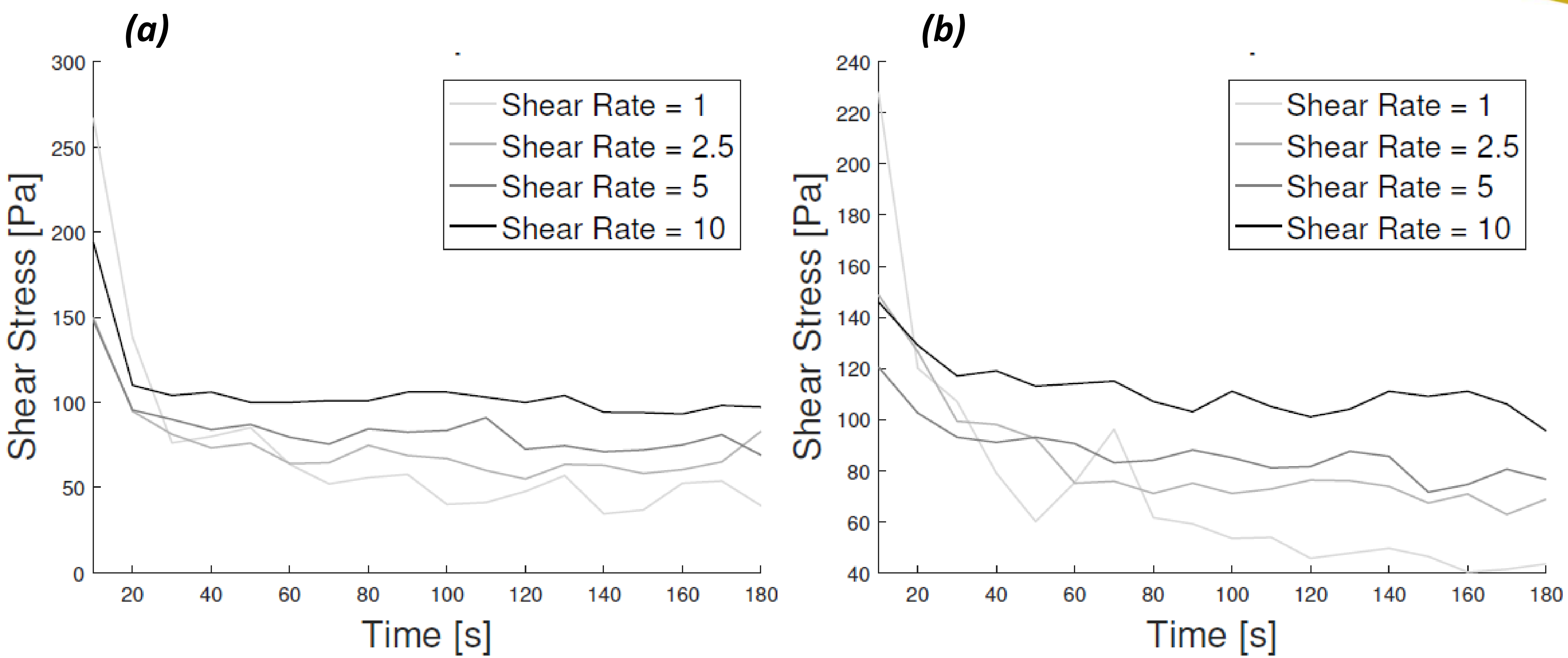


	Rheological tests
Age [min]	0, 15, 30, 60
Superplasticizer [%]	0.1, 0.15
Number of samples per set	1
Membrane	-
Buildup rate [steps]	-
Duration [sec]	180
Shear rate [1/sec]	1, 2.5, 5, 7.5, 10
Tot. number of samples	40

Test matrix.



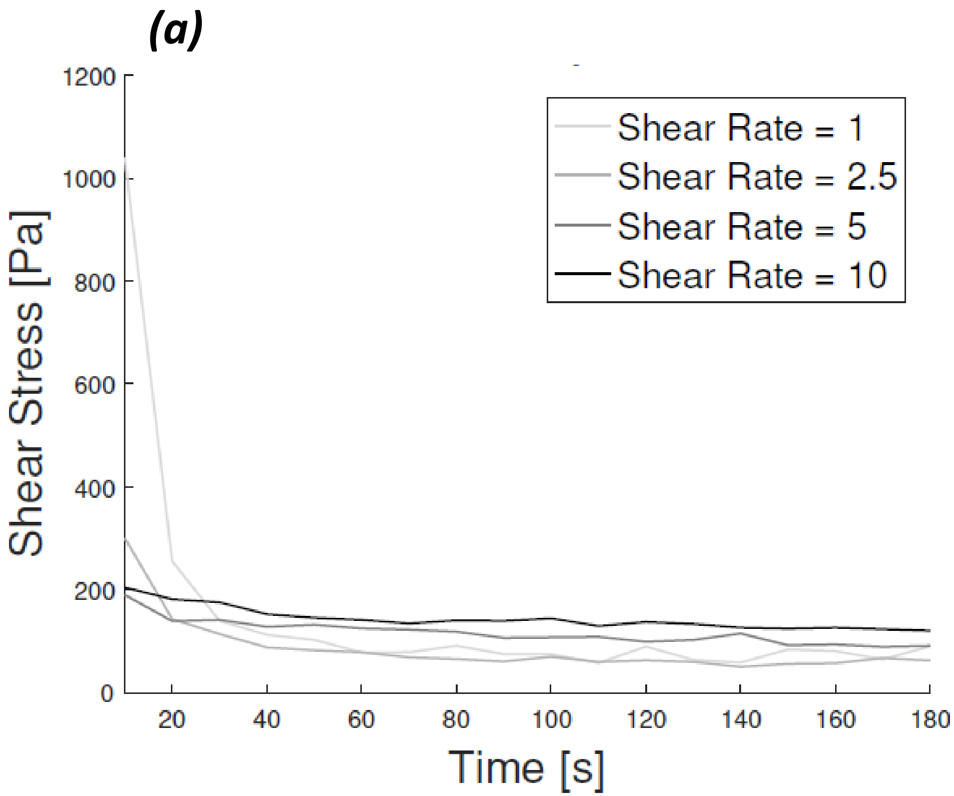
Rheological testing

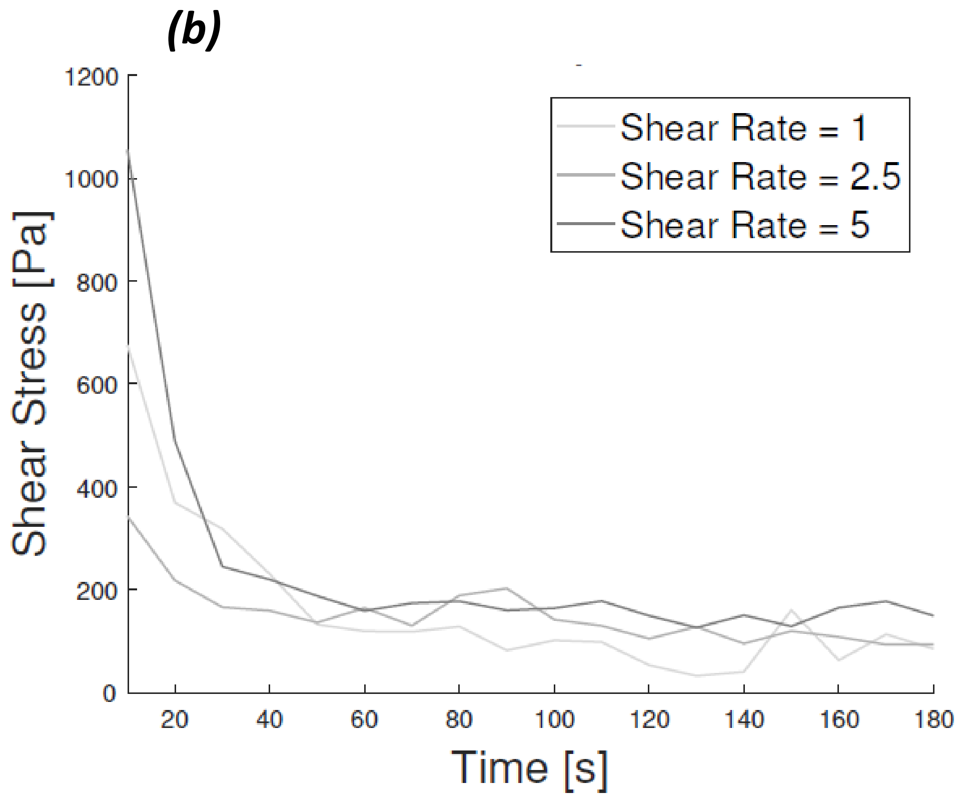


***Effect of Age*: REF-SP0.10.**
Average results at different times: (a) 0 min, (b) 15 min.

- Initially, peak is needed to onset the flow (static yield stress); consequently, peak decreases stabilizing (dynamic yield stress)

Rheological testing

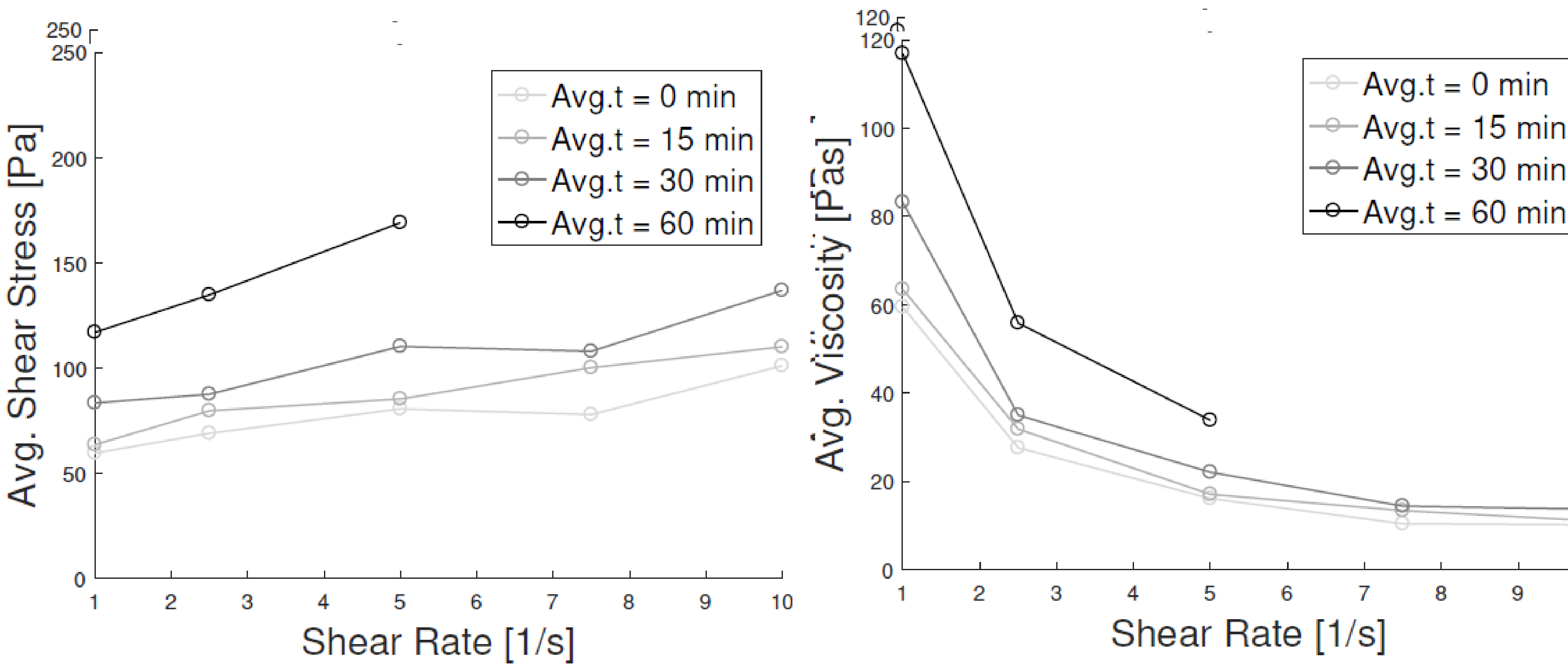




Effect of Age ***: REF-SP0.10.***
Average results at different times: (a) 30 min, (b) 60 min.

- Static and dynamic yield stress evolve in time, showing lowest amounts for fresh mixes (0.12-1.07Pa for 0.1% in cement weight)

Rheological testing

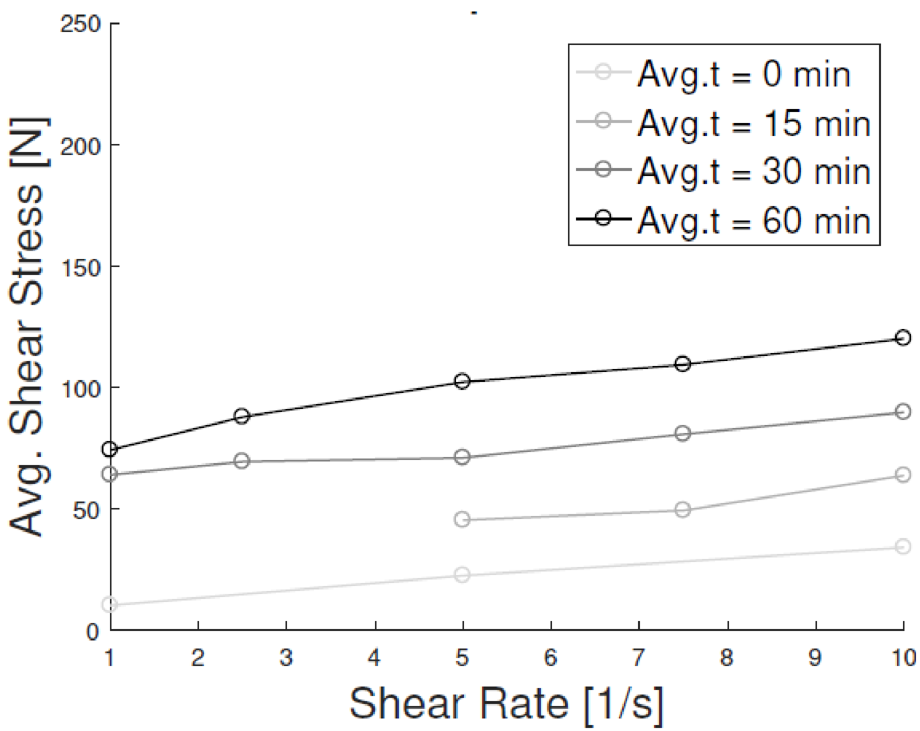


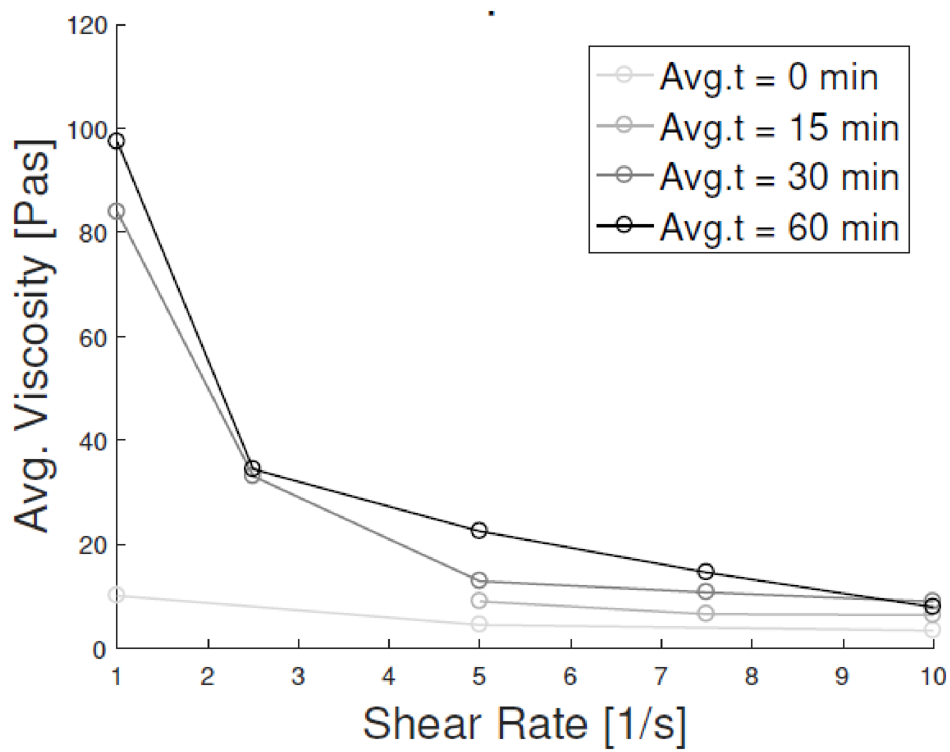
***Effect of Age*: REF-SP0.10.**

Average comparisons at different times: Avg. Shear Stress and Avg. Viscosity.

- Mix behaves as Bingham and Shear Thinning material: viscoplastic materials that react as elastic solid at low stress, but flows as viscous fluid at high stress

Rheological testing



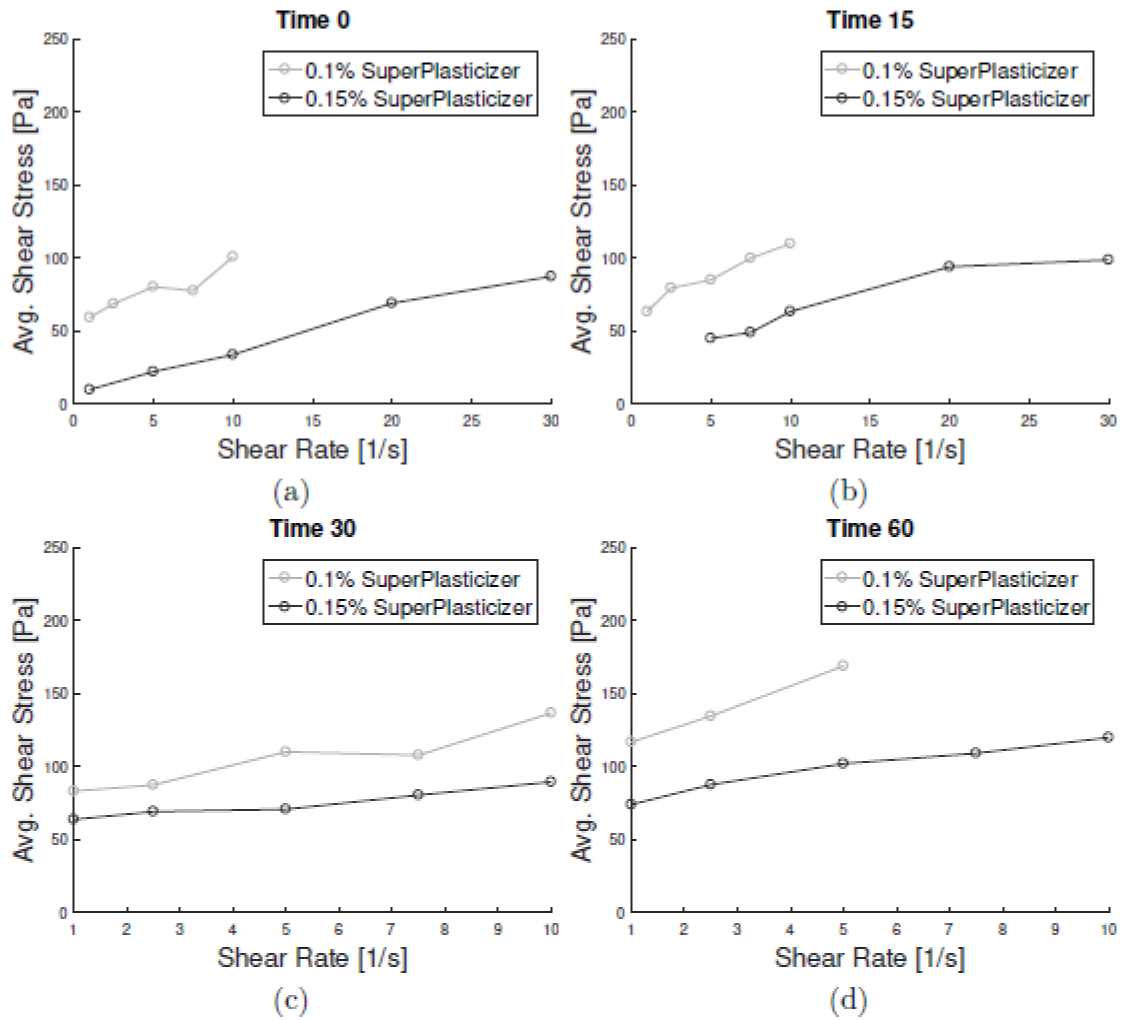


***Effect of SuperPlasticizer* : SP0.15.**

Average comparisons at different times: Avg. Shear Stress and Avg. Viscosity.

- Lowest shear strength reached at t = 0 min with 0.15% of superplasticizer
- Lowest viscosity reached at t = 0 min with 0.15% of superplasticizer

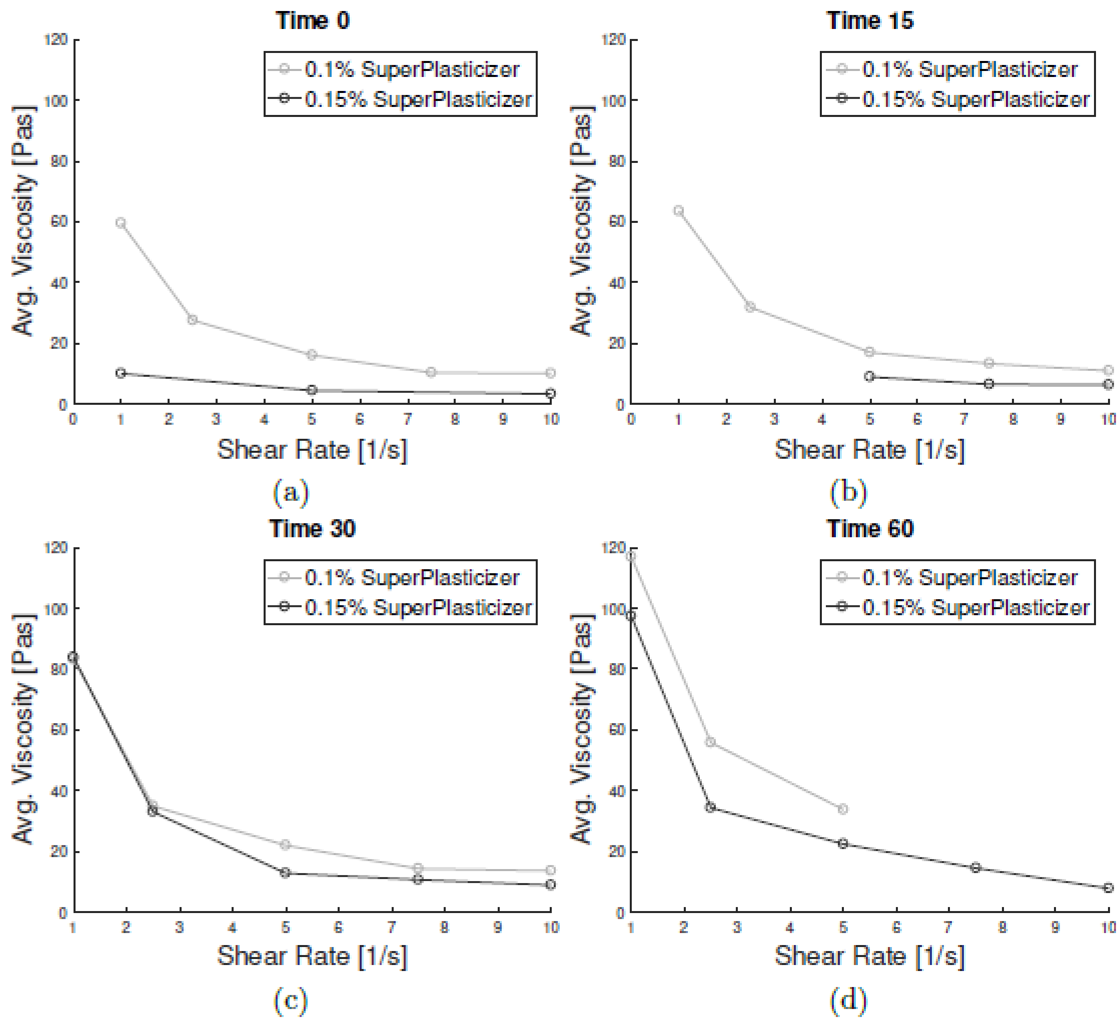
Rheological testing



Effect of SuperPlasticizer

Average comparisons at different times: Avg. Shear Stress VS Shear Rate

Rheological testing



Effect of SuperPlasticizer

Average comparisons at different times: Avg. VIscosity VS Shear Rate

Conclusions

We performed an experimental campaign composed by unconfined uniaxial compression tests, unconfined uniaxial creep tests and rheological tests.

Tests highlighted that:

- early age mechanical response is influenced by concrete resting time; as the concrete age evolves, there is an enhancement in

compressive strength (from 8.80 to 22.48 kPa)
stiffness (from 210 to 607 kPa)
plastic viscosity (from 120 to 360 Pas)
static shear strength (from 0.27 to 1.07 kPa)

Even **creep** is affected, showing a reduction (from 0.21 to 0.10 %) as mix matures

Conclusions

We performed an experimental campaign composed by unconfined uniaxial compression tests, unconfined uniaxial creep tests and rheological tests.

Tests highlighted that:

- increasing/decreasing amount of superplasticizer, **lower** strength, stiffness, viscosity and experimental precision (RSD 43.08%). Creep **grows** increasing SP and reduces decreasing SP
- without membrane there is a **decrease** in strength (from 5.44 to 3.62 kPa) and stiffness (from 124 to 68 kPa), giving rise at the most inaccurate results (RSD reached a peak of 44.75%)
- displacement rate influences stress-strain response: when the rate rises significant increment in compressive strength (up to 34.84 kPa), despite a reduction in test accuracy (RSD 40.35%);

Conclusions

Reliability of methodology strictly depends on variability of testing procedures (failure prediction fluctuation is in the range of 30-40%).

standardized procedures for material mechanical characterization → greater **confidence** in analytical/predictive models

Some recommendations may be employed to enhance reliability of testing protocol:

(i) the external membrane increases the repeatability of the test
(ii) 0.1% represents the optimal superplasticizer amount
(iii) a lower displacement rate increases the test accuracy

Such recommendations also permit a more reliable failure prediction.


Thank you for your attention!