Detailed analysis and interpretation of flow curves from round-robin tests (RRT) on concrete rheometers

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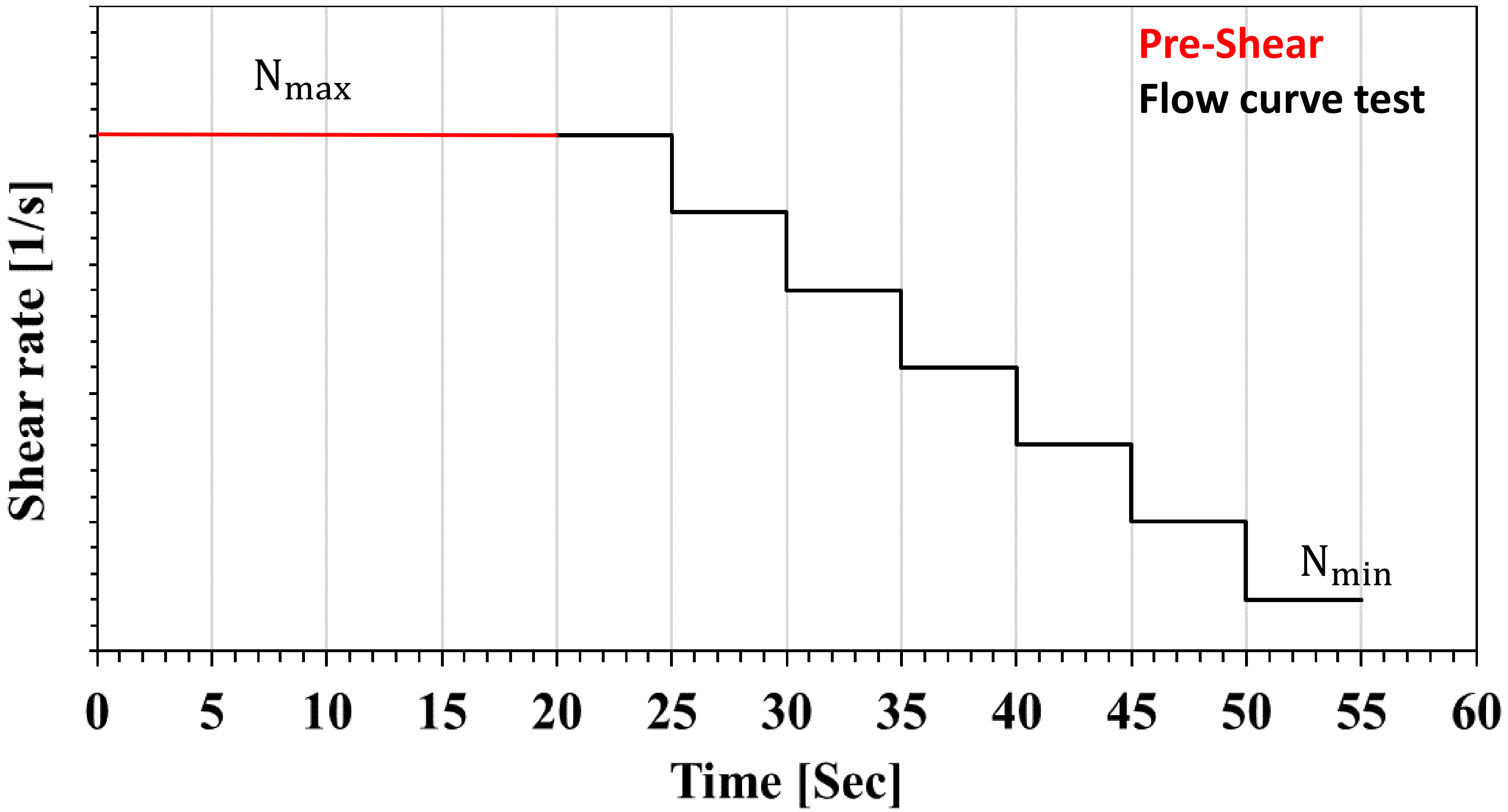
Mixtures

Concrete 1: SCC	Reference	SF = 600 mm / VF = 20 s
Concrete 2: SCC	Lower Yield Stress	SF = 700 mm / VF = 5 s
Concrete 3: SCC	Higher Viscosity	SF = 550 mm / VF > 30 s
Concrete 4: Flowable	Less Powder	SF = 600 mm / VF = 20 s
Concrete 5: Flowable	Higher Yield Stress	SF = 400 mm / Slump = 230mm
Mortar 1:	Reference	SF = 750 mm / VF = 3 s
Mortar 2:	Higher Viscosity	SF = 650 mm / VF = 5 s
Mortar 3:	Higher Yield Stress	SF = 550 mm / VF = 3 s

**No conventional mixtures were evaluated*

Procedure

Perform empty measurement: eliminate residual torque / set reference value



Procedure

	N_{max}	N_{min}
ICAR 1-3	0.500	0.025
Viskomat XL	0.540	0.027
eBT-V	0.529	0.026
Rheocad	0.570	0.028
4SCC Rheometer	0.210	0.010

No fundamental units for RheoCad Helix, so used same as RheoCad Vane.

4SCC Rheometer: arbitrary values.

Procedure

ICAR 1-3:

Pre-shear: 0.5 rps for 20 or 30s
7 steps, 5 s each

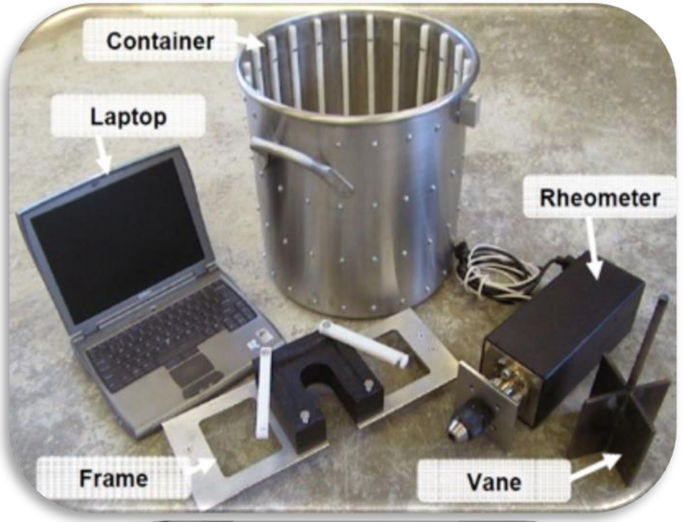
Duration: 55 – 65 s

ICAR 4:

Pre-shear: 0.5 rps for 60 s
7 steps, 10 s each

Duration: 130 s

Six Rheometers with Fundamental Data



ICAR (3)

Viskomat-XL

RheoCad (Vane)

eBT (Vane)

Six Rheometers with Fundamental Data

Maximum 24 flow curves, except for RheoCad, which had 16.

Results were only eliminated according to established criteria.

So, how do we get a reference value to compare all rheometers to?

- Take 1 rheometer? Which one? Why? What if a certain measurement is wrong, or is eliminated?
- Take 3 ICAR rheometers? Why would these be better than the others? Considerable spread on data
- Take the average? But some rheometers delivered more test results than others

The Baseline: A weighed average

Initial step:

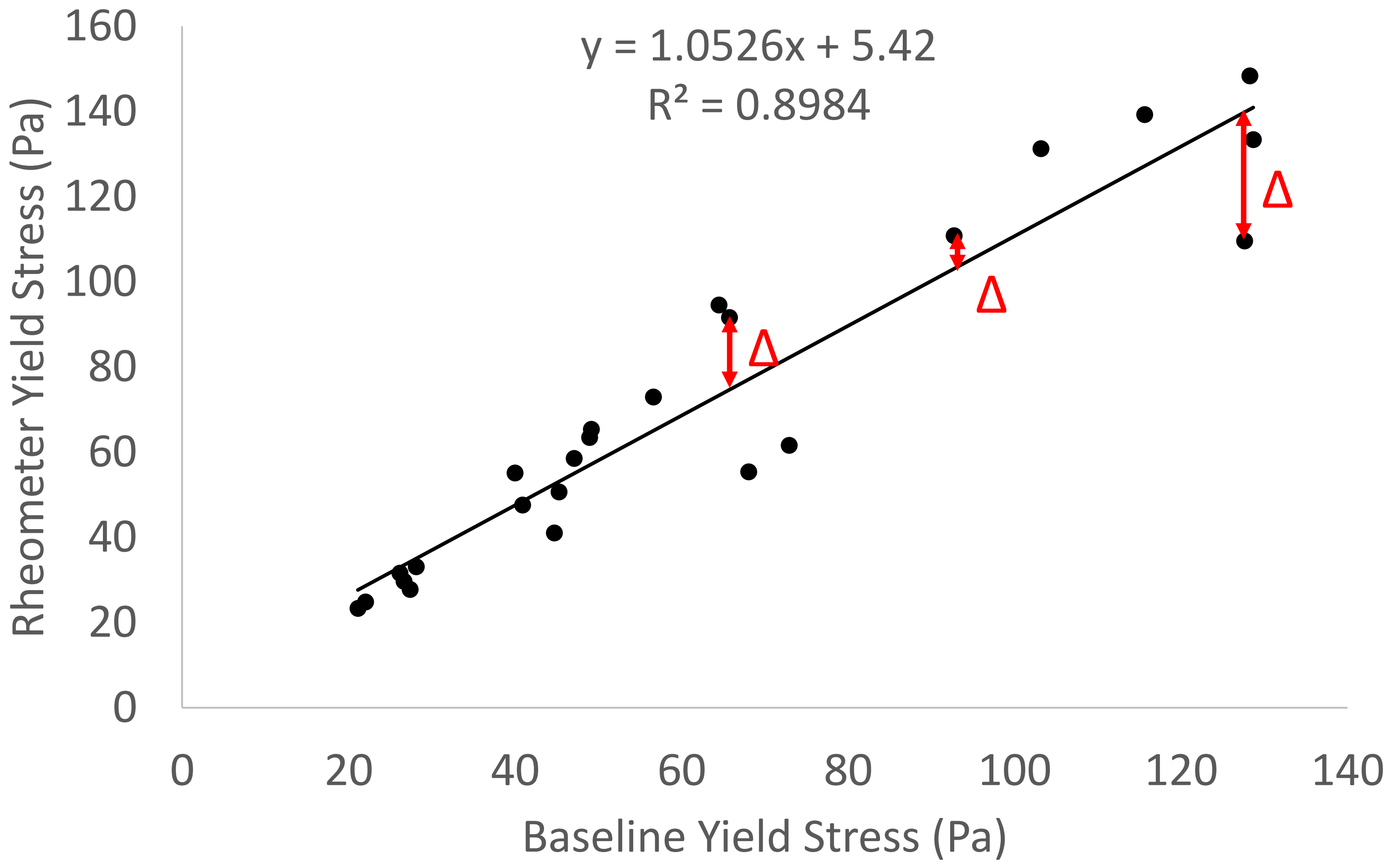
Two weighing factors, giving more importance to certain test (mixture – time) and certain rheometers.

- For each rheometer: # of tests included (max. 24)
- For each test: # of rheometers with a valid test result (max. 6)

Calculate weighed average for each test. Determine linear correlation between each rheometer and the baseline.

The Baseline: A weighed average

Determine difference between each rheometer value and the corresponding value based on the correlation at equal baseline value (Δ).



The Baseline: A weighed average

Determine standard deviation of Δ-values for each rheometer, separately for yield stress and viscosity.

Remove outliers on Δ based on a 90% confidence interval.

- Measurements with high Δ compared to other measurements (on the same device) are eliminated – more accurate results
- However, more measurements are eliminated for rheometers with smaller standard deviations – reduced weight for rheometers producing more uniform measurements.

Recalculate standard deviation on Δ and use as additional weighing factor for each rheometer.

The Baseline: A weighed average

Initial step:

1/ Two weighing factors.

- For each rheometer: # of tests included (max. 24)
- For each test: # of rheometers with a valid test result (max. 6)
- Determine linear correlation between rheometer and baseline

2/ Outlier analysis on Δ for each rheometer, separate for YS and PV

3/ Recalculate St Dev. on Δ and use as additional factor for each rheometer (separate for YS and PV)

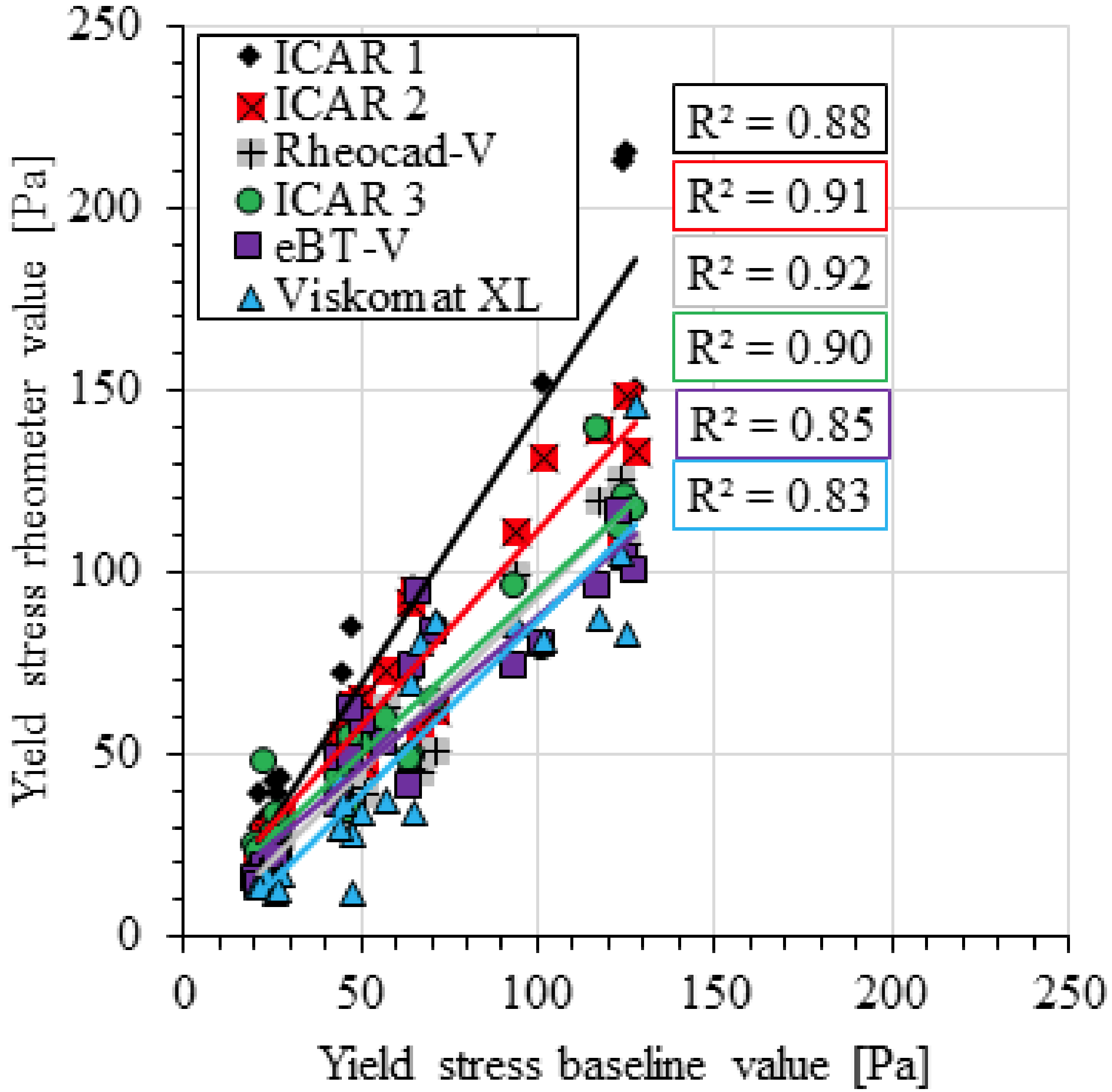
Repeat iteration until no more outliers (4 iterations).
Recalculate baseline with last St. Dev. on Δ.

Yield Stress

Strong correlations for each rheometer with the baseline.

ICAR 1-2 delivers **highest** values (max 1.5), Viskomat-XL and eBT-V deliver **lowest** values (min 0.8).

Assumed to be related to calibration settings in rheometer



Plastic Viscosity

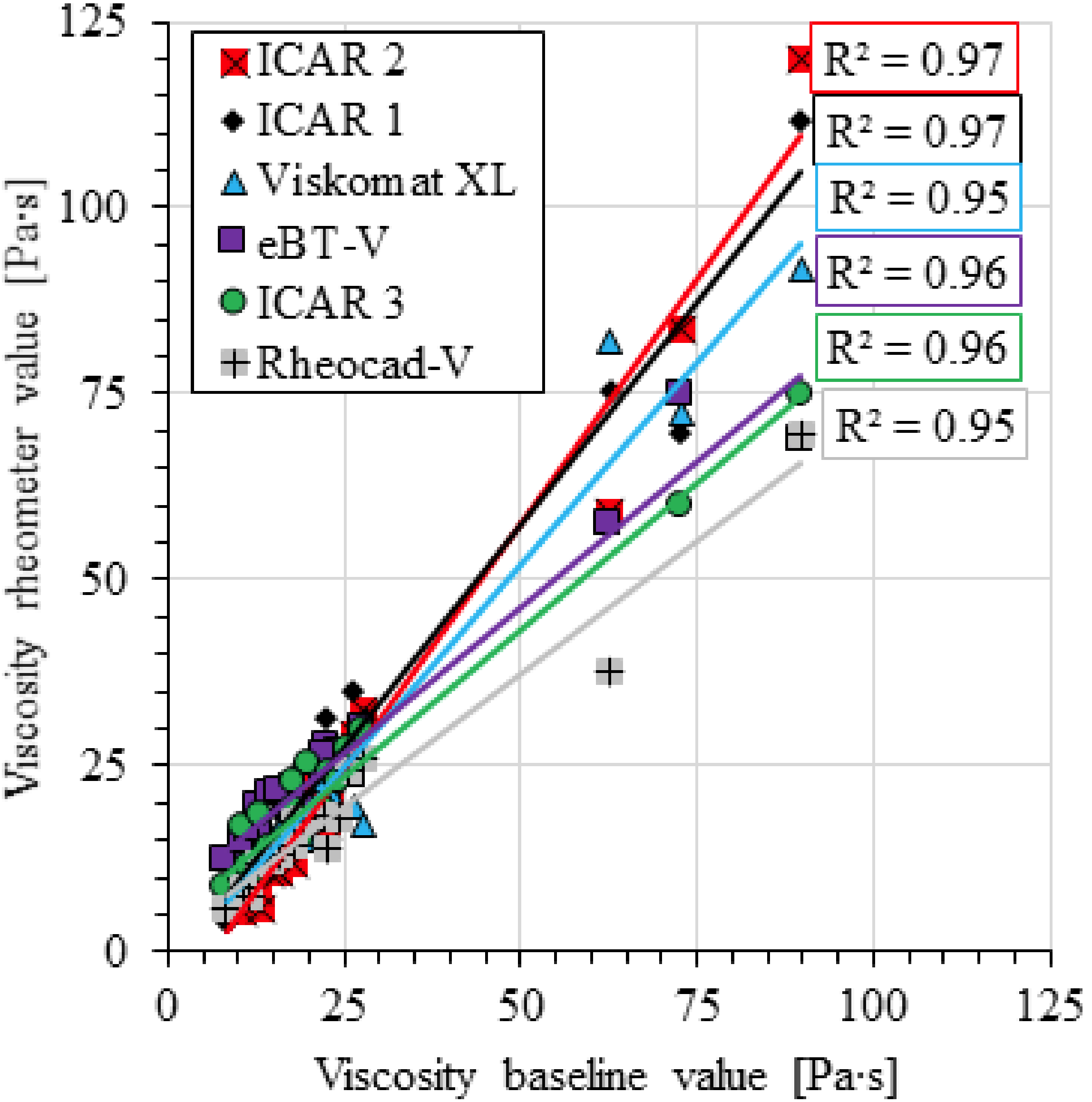
Excellent correlations for each rheometer with the baseline.

ICAR 1-2 delivers **highest** values (max 1.3), ICAR 3 and RheoCad deliver **lowest** values (min 0.7).

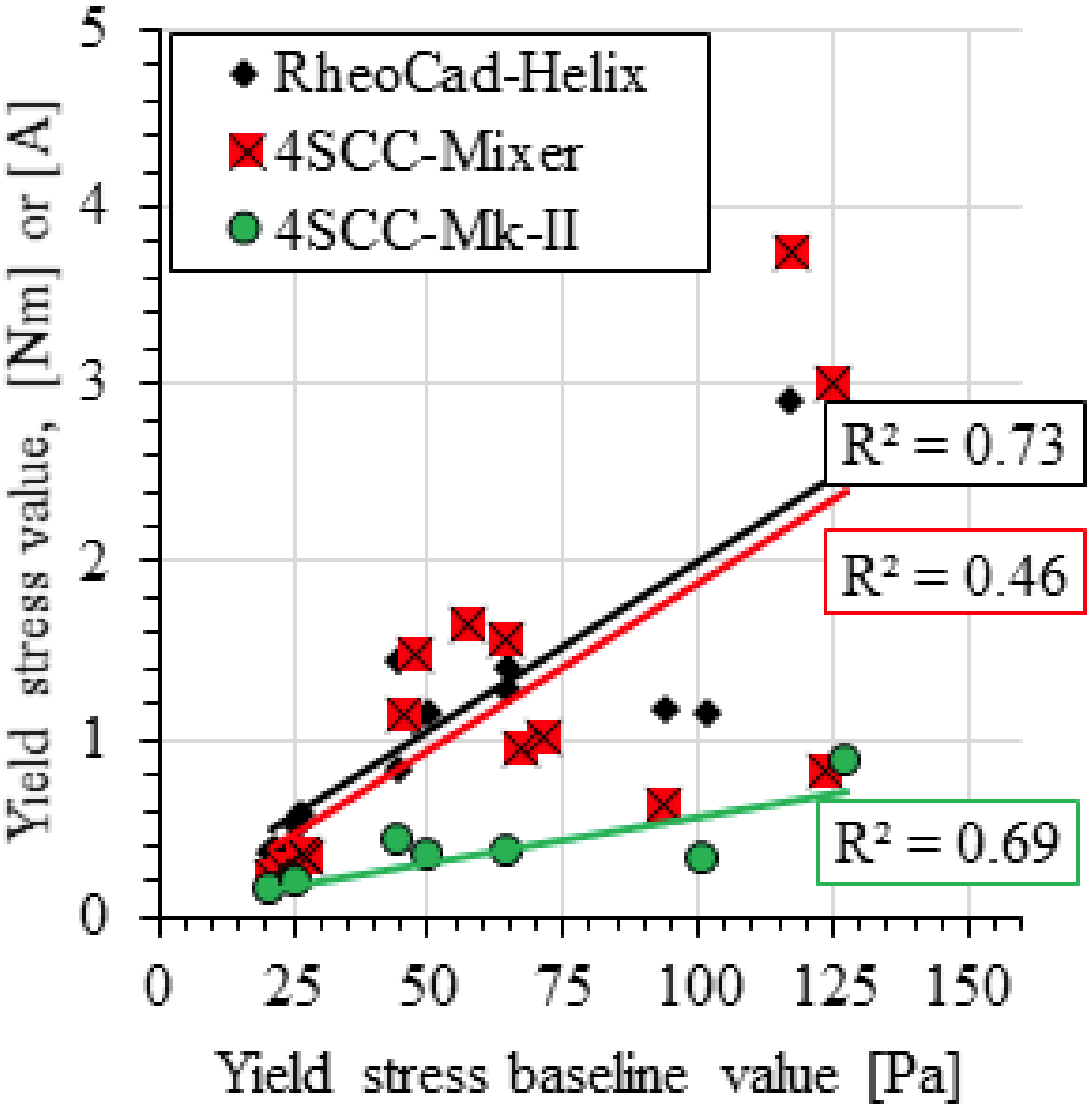
Assumed to be related to calibration settings in rheometer:

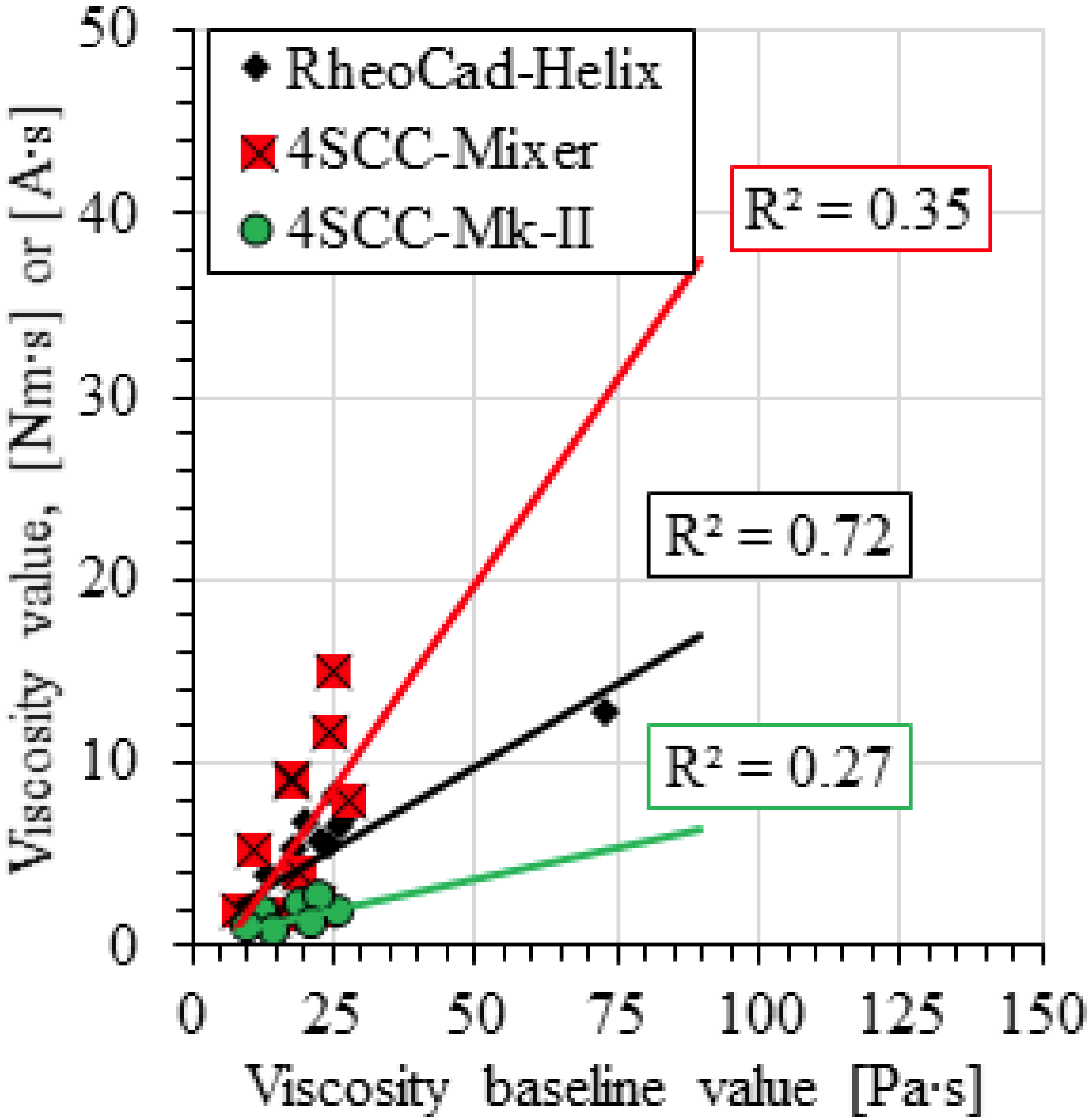
- Torque
- Velocity

Considerable differences noted, but strong correlations point that rheometers assess mixtures similarly



Rheometers with Relative Units





Sensitivity: Deviation from Correlation

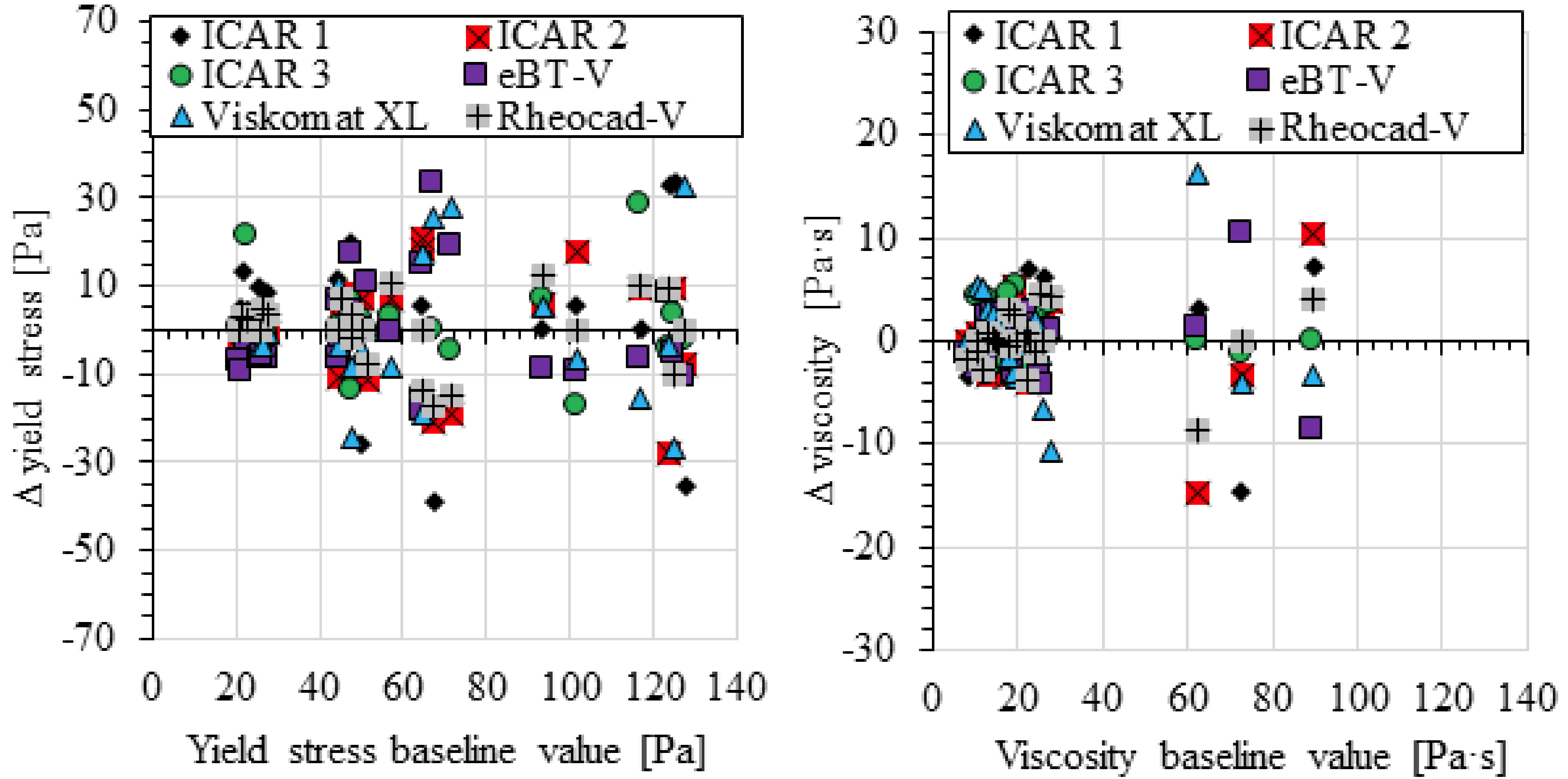
Calculate Δ values: difference between rheometer test and correlation with baseline.

For each rheometer (separate for YS and PV), average Δ is zero.

Standard deviation for Δ can be an indicator on how much a rheometer deviates from its trendline, and thus reveal if a rheometer struggles to deliver consistent measurements or not.

However, Δ is calculated as an absolute deviation, not as a relative value, which may disadvantage the rheometers with larger slopes. To eliminate this, we have divided the St. Dev. on Δ by the slope of YS or PV with the baseline.

Sensitivity: Deviation from Correlation



Sensitivity: Deviation from Correlation

	Rel. St. Dev. Δ YS	Rel. St. Dev. Δ PV
ICAR 1	13.6	4.1
ICAR 2	11.3	3.5
ICAR 3	12.2	3.8
Viskomat XL	14.7	4.5
eBT-V	16.0	4.7
Rheocad	10.1	4.8

No real differences between rheometers

Sensitivity: Deviation from Correlation

	St. Dev. Δ YS	St. Dev. Δ PV
Concrete 1	17.7	4.1
Concrete 2	7.5	3.0
Concrete 3	11.4	9.3
Concrete 4	18.7	5.0
Concrete 5	20.7	1.3
Mortar 1	7.2	2.1
Mortar 2	5.4	2.0
Mortar 3	13.9	2.4

Sensitivity: Deviation from Correlation

Mixture type has more influence on precision of measurement compared to the selected rheometers.

For yield stress, more deviation from the correlation is noted with:

- Increased coarse aggregate content
- Increased YS/PV

For plastic viscosity, more deviation from the correlation is noted with an increased plastic viscosity.

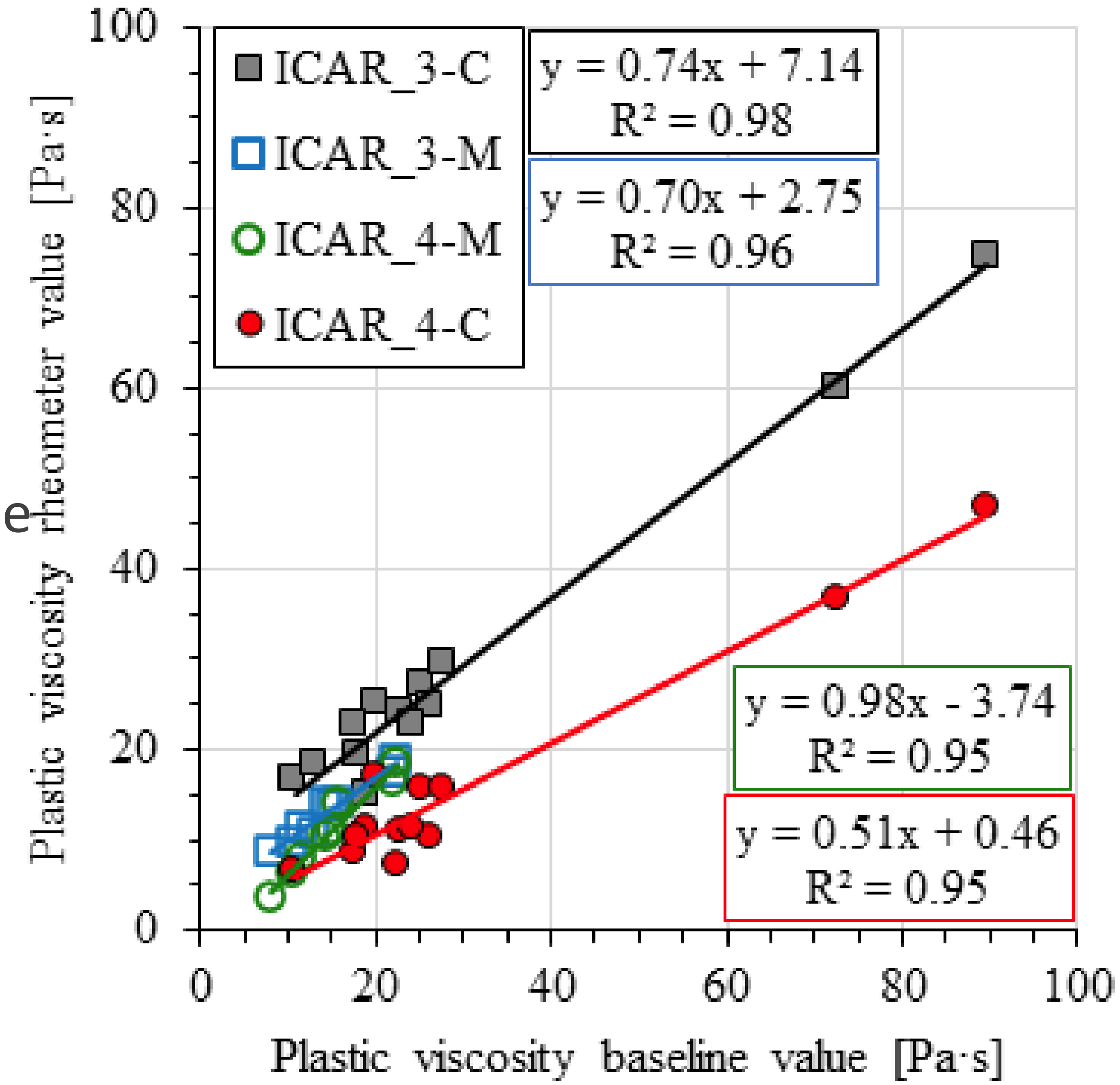
What about that longer measurement?

Risk: Enhanced shear-induced particle migration in concrete (less in mortar)

Assume mortar is not affected: find slope with baseline (blue / green).

If concrete is unaffected, slope with baseline should remain unaffected (black / red).

For ICAR 3 (55 s measurement), slope remains approximately constant
For ICAR 4 (130 s measurement), slope decreased drastically for concrete



Summary

A complex averaging calculation was performed to remain as objective as possible in establishing the baseline values for yield stress and viscosity.

All rheometers for which fundamental units can be calculated show strong correlations with the baseline, but significant differences (up to a factor 2) can be noted. This is attributed to the calibration settings of each device.

No differences appeared between rheometers in how precisely they measure values relative to the correlation with the baseline.

Summary

The mix design did have a more notable effect on the deviations of each measurement compared to the correlation with the baseline.

- Yield stress was affected by coarse aggregate content and YS/PV.
- Higher viscosity values increased deviations on viscosity.

If we would extrapolate this finding, it means that measuring the rheological properties of conventional vibrated concrete would experience even more concerns on precision.

Extended measurement durations on concrete mixtures can lower the measured viscosity due to shear-induced particle migration.

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