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Norwegian Building Research Institute

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Frost testing of porous and recycled aggregates

NORDTEST Project 1440-99
Technical Report 458

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Summary

A Nordic round robin test project was carried out on the prEN 1367-1 frost test for aggregates. The objective was to clearify the effect of deicer salt (which is not normative in EN 1367-1, but considered very relevant for Nordic exposure conditions) and predrying procedure on test results for recycled and porous aggregates. Four laboratories participated (NBI (coord.), RB, VTT, SP) in the round robin test with 4 different aggregates (1 recycled concrete, 1 porous artificial expanded clay and 2 Icelandic volcanic rocks). The materials were freeze/thaw tested in deionized water and 1% NaCl-solution after 3 different predrying procedures (105°C, 40°C and "no" predrying). The results show that severe predrying and salt solution may increase or reduce frost damage depending on the type of aggregate. RCA appears to be most susceptible to both severe predrying and deicer salt. Salt may also be negative for natural LWA, whereas predrying appears to have no negative effect on frost damage of artificial and natural LWA. Several experimental details varied between the laboratories, especially on predrying procedure, affecting the results. This is partly due to deviations from test procedures, and partly due to variations allowed within the test procedures. Because of the latter and the very negative effect that severe predrying has on test results for recycled aggregate, recommendations for drying procedure, saturation and calculation of damage are given for the application of prEN1367-1 to porous and recycled aggregate.

1 Introduction

Aggregate is the main building material in the building and construction industry measured in bulk volume or mass. As a rough figure we estimate the annual aggregate consumption in the Nordic countries to be 300 million tons. Porous aggregates such as artificial lightweight aggregates (LWA) and various waste materials such as recycled aggregates (RCA) are increasingly used on behalf of natural aggregates. LWA for example, is used in unbound applications in the Nordic countries due to beneficial properties such as their low weight and insulating properties.

In the work of CEN TC 154 Aggregates, LWA, RCA and natural porous aggregates are handled in several sub committees. One basic principle of TC 154 is that common test methods apply to all kinds of aggregates, whether natural, artificial, or based on various waste materials. Freeze/thaw resistance, which is one very important durability property for aggregates in the Nordic countries exposed to freezing in saturated condition, can be tested according to prEN-1367 [1]. In [1] freeze/thaw testing of aggregate is performed on a defined size fraction submerged in water for 10 consecutive daily cycles. Measuring the amount of material passing a sieve with a nominal opening size half of the initial minimum size (4 mm when testing the 8 - 16 mm fraction) after 10 freeze/thaw cycles assesses the frost damage. Prior to freeze/thaw the test portion is dried at 105 °C and saturated for 24 hours with the actual test liquid.

The proposed test method for freeze/thaw [1] has been criticised in the CEN work, initially by Iceland, not to reflect the severe climatic conditions of the Nordic countries since deicer salt solution is not a normative test liquid. The use of 1 % NaCl as test liquid instead of water is given only as an informative annex in [1].

A Nordtest project co-ordinated by Iceland (RB) was carried out to investigate this further [2]. The Nordtest method proposed in [2] accounts for the more severe climate in the Nordic countries by using 1 % NaCl, in contrast to the European test [1].

New research [3,4] has also shown that the drying procedure prior to freezing in the proposed European aggregate frost test [1] can influence the frost damage of recycled concrete aggregate. Freezing and thawing after natural drying was found to give lower damage than when dried according to [1], i.e. at 105°C.

In order to investigate the influence of salt solution and elevated pre-drying procedures on the frost damage of porous and recycled aggregates, a research program was established involving four Nordic research laboratories carrying out a round robin test (RB – Iceland, SP – Sweden, VTT – Finland and NBI – Norway (coordinator) . The test results will be used to evaluate the present Nordtest (and European) test method and to give recommendations for revisions to [1].

2 Research program

2.1 Testing and materials

Four different porous aggregates were tested according to three different predrying procedures before resaturation and frost exposure in water or 1% NaCl:
D1: 105°C in ventilated oven for 24h
D2: 40°C in ventilated oven for 24h
D3: no predrying (saturation and testing "as received")

The test program can be seen in appendix 1.

The materials tested were:
- Leca – LWA
- Recycled aggregate – RCA
- Nat 1
- Nat 2

Leca is an expanded clay aggregate produced in a rotating kiln. The recycled aggregate was taken in Norway from the recycling plant of BA Gjenvinning in Oslo, and was a mix of crushed concrete, tile and asphalt. These were collected prepared and distributed by NBI.

Nat 1 and Nat 2 are two types of natural Icelandic aggregate (normal). Nat1 is a fresh, porous, pillow lava from the Reykjavik district. Nat2 is an acidic, light weight, pumice originated from Mt. Hekla. Both Nat1 and Nat2 were collected, prepared and distributed by RB.

A test procedure was sent by NBI to the participating laboratories, see appendix 2. Also worksheets with the appropriate formulae (density, absorption and F - see section 2.2 and 3.3.) adjusted to the individual test programme of each laboratory were made at NBI and sent out before start of testing.

2.2 How to determine frost damage

Frost damage is in [1] expressed by the percentage mass loss (F) after freeze / thaw exposure:

$$F = 1 - \frac{M_2}{M_1} \cdot 100\%$$

Where, M_1 : initial dry (105°C) mass of the test specimen before cycling (g).
M_2 : final dry mass (105°C) after cycling that is retained on the specified sieve, (g).

Here we have to calculate the corresponding 105°C dry mass (before cycling) of the undried (D3) and 40 °C dried samples (D2). This is done by taking into account the water absorption at 105°C ($abs._{105}$) and 40°C ($abs._{40}$) measured on parallel samples. Frost damage is thereby expressed by the following equations:

$$F_{0,D1} = 1 - \frac{M_2}{M_1^1} \cdot 100\%$$

$$F_{0,D2} = 1 - \frac{M_2}{M_1^2 \cdot (\frac{1+abs._{105}}{1+abs._{40}})} \cdot 100\%$$

$$F_{0,D3} = 1 - \frac{M_2}{M_1^3 \cdot (\frac{1}{1+abs._{105}})} \cdot 100\%$$

where,

$F_{0,D1}$: percentage loss in mass of aggregate pre dried at 105 °C
$F_{0,D2}$: percentage loss in mass of aggregate pre dried at 40 °C
$F_{0,D3}$: percentage loss in mass of aggregate without any pre drying
M_1^1: mass of test specimen dried at 105 °C before cycling (g)
M_1^2: mass of test specimen dried at 40 °C before cycling (g)
M_1^3: mass of test specimen without any predrying before cycling (g)
M_2 : final dry mass (105 °C) after cycling that is retained on a 4 mm sieve (g)
$abs._{40}$: water absorption of aggregate dried at 40 °C$abs._{105}$: water absorption of aggregate dried at 105 °C

$$abs._{40} = \frac{m_1 - m_{40}}{m_{40}}$$

$$abs._{105} = \frac{m_1 - m_{105}}{m_{105}}$$

where,

m_1 : mass of surface dried aggregates after 24 h soaked in test liquid (g)
m_{40} : mass of aggregates dried at 40°C for 24 h after soaking (g)
m_{105} : mass of aggregates dried at 105°C for 24 h after soaking (g)

As an alternative way to determine F it was suggested to collect, dry and weigh both deteriorated material (<4mm) and material retained on the 4mm sieve. This however was by most laboratories found to be difficult in practice (difficulties by collecting aggregates less than 4mm during sieving/washing operations), and therefore left out. Frost deterioration determined this way was denominated F_t:

$$F_{t,D1\text{-}D2\text{-}D3} = (1 - \frac{m_{>4mm}}{m_{>4mm} + m_{<4mm}}) \cdot 100\%$$

where,

$m_{>4mm}$: mass of aggregates larger than 4 mm after freeze /thaw dried at 105°C, in grams
$m_{<4mm}$: mass of aggregates smaller than 4 mm after freeze /thaw dried at 105°C, in grams

3 Results

3.1 Frost damage

All test-results can be found in appendix 3. In table 1 a-d the frost damage is expressed as the average of three parallel boxes. In some cases the test procedure used deviated so much compared to the scope of the project, that the results have been taken out of the tables, see evaluation in section 4.3 and 4.4.

Sample	*$F_{average}$ [%]*		*Sample*	*$F_{average}$ [%]*	
	NBI	VTT		NBI	SP [2]
D1-W	3,9	9,4[1] (6,8)	**D1-S**	1,1	0,3
D2-W	3,5	3,4	**D2-S**	1,7	-
D3-W	8,7	8,5	**D3-S**	2,0	-

Tab.1a – **LWA specimens** (Leca)

[1] Stdv = 4,76! 6,8% represent the average of the two specimens with the lowest degree of damage, still with a standard deviation of 1,5.

[2] Deviation from drying procedure, all material dried at 105°C (D1) before freeze / thaw. F_t values used.

Sample	*$F_{average}$ [%]*		*Sample*	*$F_{average}$ [%]*	
	NBI	VTT		NBI	SP [1]
D1-W	7,2	7,2	**D1-S**	25,4	26,8
D2-W	4,2	4,2	**D2-S**	23,5	-
D3-W	2,4	3,7	**D3-S**	18,2	-

Tab.1b – **RCA specimens**

[1] Deviation from drying procedure, all material dried at 105°C before soaking and freeze / thaw. F_t values used.

Samples	*$F_{average}$ [%]*		*Samples*	*$F_{average}$ [%]*	
	RB [1]	SP [1)3)]		RB [1]	VTT [1]
D1-W	0,4	0,2	**D1-S**	2,1	3,4
D2-W	0	-	**D2-S**	2,5	3,2
D3-W	- [2]	-	**D3-S**	- [2]	4,7

Tab.1c – **Nat 1 specimens**

[1] F_t values used

[2] Did not perform freeze / thaw in a wet condition

[3] Deviation from drying procedure, all material dried at 105°C before soaking and freeze / thaw.

Samples	*$F_{average}$ [%]*		*Samples*	*$F_{average}$ [%]*	
	RB [1]	SP [1)3)]		RB	VTT [1]
D1-W	7,1	6,8	**D1-S**	1,3	0,3
D2-W	32,6	-	**D2-S**	-2,1	5,2
D3-W	- [2]	-	**D3-S**	- [2]	11,0

Tab.1d – **Nat 2 specimens**

[1] F_t values used

[2] Did not perform freeze / thaw in a wet condition

[3] Deviation from drying procedure, all material dried at 105°C before soaking and freeze / thaw.

In several cases F was negative when using the formulas in section 2.2. We could not find the cause for these negative values (probably related to drying procedure). In these cases we used F_t as defined above.

3.2 Water absorption and dry particle density

Water absorption values were determined on two test specimens. The results are presented in table 2a-b.

Test material	Water absorption - Abs.105 (g/g dry)							
	NBI		RB		VTT		SP	
	W	S	W	S	W	S	W	S
LWA	0,096	0,094	-	-	0,123	-	-	0,11
RCA	-	-	-	-	0,076	-	-	0,064
NAT1	-	-	0,067	0,060	-	0,065	0,03	-
NAT2	-	-	1,154	1,154	-	1,187	0,68	-

Table 2a – Abs_{105}

Test material	Water absorption - Abs.40 (g/g dry)							
	NBI		RB		VTT		SP	
	W	S	W	S	W	S	W	S
LWA	0,096	0,095	-	-	0,123	-	-	0,099
RCA	-	-	-	-	0,027	-	-	0,032
NAT1	-	-	0,053	0,050	-	0,062	0,03	-
NAT2	-	-	0,201	0,200	-	0,216	0,68	-

Table 2b – Abs_{40}

The dry particle density (D_{dry}) was determined on one specimen. The results are given in table 3.

$$D_{dry} = \frac{m_{sat}}{V}$$

where, m_{sat} is the mass of the aggregates soaked for 24h in water (surface dried) (Kg)
V is the volume of the aggregates (m^3)

Test material	Dry (105°C) particle density - Kg/m3			
	NBI	RB	VTT	SP
LWA	559,3	-	477,3	495,0
RCA	2148,0	-	1621,0	2224,0
NAT1	-	2884,0	2437,0	2415,0
NAT2	-	476,0	518,1	541,4

Table 3 – Dry particle density

4 Discussion

4.1 *Effect of predrying*

The effect of the predrying procedure described in EN 1367-1 on the frost performance is not quite clear. In some cases (cement based aggregates – RCA) the predrying severely reduced the test performance. However, for other materials (artificial, porous aggregate – LWA and some natural, porous aggregate – Nat1 and Nat2), it may have improved the test performance.

4.2 *Effect of 1% NaCl*

The effect of salt can be either positive (LWA and Nat2) or negative (cement based and Nat1) for the frost performance when tested according to EN1367-1. The degree of saturation obtained during testing is probably the main factor and this needs further investigation. Some additional measurements of the water content at start (after absorption) and at the end of the frost test will be advisable.

For LWA it is probable that a reduced degree of saturation is the reason for reduced frost damage after drying.

4.3 *Density and water absorption*

These values show a very large scatter as a clear proof that either the test procedures were not equal (see section 4.4 and 4.5) or that calculation errors occurred that we have not been able to detect in this test.

4.4 *Deviations from test procedure*

Even though the test procedure was described and distributed to all participating laboratories, some deviations occurred, partly due to misunderstandings and sickness of key personell:

- NBI did not determine water absorption on RCA specimens, and therefore used the absorption values measured at VTT to calculate the initial dry mass (105°C) of the D2 and D3 specimens. NBI did not specify the correct figures in tab. 1 in appendix 2 – test procedure. The correct values should be 1000 g Nat 1 and 300 g Nat 2.

- RB: The D3 specimens were not soaked in a wet condition during freeze/thaw. The mass of the test-specimens was not in accordance with that described in test procedure (table 1). After freeze/thaw, the aggregates were dried for 24 hours and not too constant mass.

- SP dried all material at 105°C prior to freeze / thaw. In some specimens the mass of the aggregates was not in accordance with that described in test procedure. After freeze/thaw, D1 and "D2"-specimens were dried for only 24 hours. The D3-specimens where dried during one weekend.

- VTT: In some specimens the mass of the aggregates was not in accordance with that described in test procedure (prior to freeze / thaw). All specimens were dried for 24 hours after freeze/thaw.

4.5 Differences in test procedures

The test procedure did unfortunately not specify all actions sufficiently detailed. Thereby some differences in procedures were made:

- NBI dried all specimens in metal boxes. After freeze / thaw only aggregates larger than 4 mm were collected and weighed. It was not possible to have an accurate measure of aggregates smaller than 4 mm. This is the normal procedure. See LA-test.

- RB dried all specimens in "heaps" in rather small trays. RB used 1000 g Nat 1 in the test.

- SP dried all specimens in thin layers. After freeze / thaw both aggregates smaller than 4 mm and aggregates larger than 4 mm were collected and weighed. SP used 2000 g Nat 1 in the test.

- VTT dried all specimens in metal boxes. After freeze / thaw both aggregates smaller than 4 mm and aggregates larger than 4 mm were collected and weighed, but the latter was just performed on Nat2 specimens. VTT used 2000 g Nat 1 in the test.

To sum up 4.4 and 4.5 it can be stated that part of the deviations between the different laboratories are due to deviations in test procedures and partly due to differences in test procedures that are allowed within the specification. The latter point needs improvement, and recommendations are given later in this report for the use of the test for porous aggregate.

4.6 Scatter

A statistical evaluation of the repeatability and reproducibility according to ISO 5725 was not performed due to the above mentioned deviations in laboratory procedures. However, a plot of mean frost damage vs. coefficient of variation (3 parallel specimens) was made. The result is shown in figure 1 below and indicates that the common relationship between mean value and standard deviation exists, and at a similar level as observed in other frost test methods.

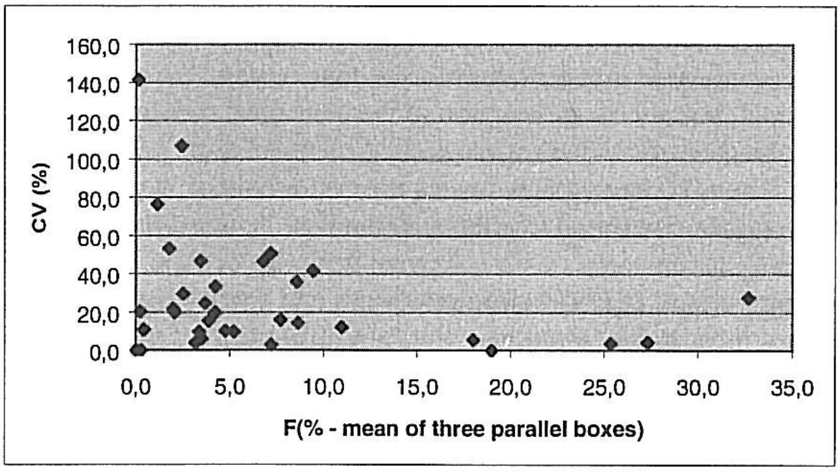

Figure 1 – Frost damage vs. coefficient of variation (3 parallel specimens).

5 Conclusions

The predrying procedure described in prEN 1367-1, before the aggregate sample is soaked and exposed to freeze/thaw, has quite different effects on the frost deterioration of various aggregate materials. For recycled aggregates (RCA) with cement based material the predrying severely reduces their test performance. Artificial porous aggregate and some natural porous aggregates, however, may in fact have improved test performance when frost testing after predrying. Also, the drying obtained during 24 h for porous materials may vary within wide ranges depending on whether the aggregate is dried in the cans, in thin layers or in heaps, and also on their porosity and moisture content before drying.

Also the effect of 1% NaCl solution on frost damage compared to damage with pure water depends on the type of porous aggregate tested. For RCA and one natural porous aggregate (Icelandic acidic pumice) 1 % salt increased the damage, whereas for LWA (Norwegian expanded clay) and another natural porous aggregate (Icelandic fresh pillow lava) the damage was reduced with salt.

Therefore, measuring the frost durability of porous aggregates with EN1367-1 needs a better description. Furthermore, the negative effect of drying for cementbased materials may exclude materials that may work well under natural conditions were they are not exposed to very severe drying before frost exposure.

6 Recommendations

The results of this study indicate that when frost testing porous aggregate with water or 1% NaCl, more precise descriptions are needed on drying and saturation before test and calculation of damage after test. Based on this project the following recommendations are given for design of test before it is used for various porous aggregates:

- Drying procedure. We do not recommend oven-drying of porous aggregates before test. However, if the 24 hour drying that is used today is to be maintained for porous aggregates, it is very important to dry in thin layers. In this case we recommend that drying of porous aggregates prior to resaturation and freeze/thaw should be carried out by spreading the aggregates in a thin layer (max 20 mm thickness) in the drying oven. Drying is then performed for 24 hours or to constant mass. Since the drying capacity of ventilated ovens may vary largely, it is better to dry to constant weight.
- Saturation. It is recommended that presaturation is done beyond the capillary nick point of the aggregate/material, simply by submersion in the cans until constant mass is reached. Constant mass can be defined as mass when weight increase during 24 hours is less than 0,1 % of dry mass. Then, 10 freeze/thaw cycles are carried out as in prEN1367-1.
- Calculation of damage. It was found that the way damage is measured and calculated is important, particularly for materials with unknown dry mass at start, i.e. materials that are not dried to constant mass at 105 °C before saturation and freeze/thaw. We recommend that both scaled (< 4 mm) and retained material (> 4 mm) must be collected after freeze/thaw. These are then dried to constant mass at 105 °C and Frost damage expressed as F = 100 % x (material < 4 mm)/(material < 4mm + material > 4mm).

7 References

[1] prEN 1367-1 Tests for thermal and weathering properties of aggregates – Part 1: Determination of resistance to freezing and thawing, Final draft december (1998) 11 p.

[2] Petursson P.: Frost resistance on aggregates: Intercomparison of a new Nordtest method: a base for CEN standardization, Final report, Icelandic Building Research Institute (1996)

[3] Jacobsen S., et al.: Properties and frost durability of recycled aggregates and -concrete from Oslo, Norway. Proceedings Sustainable construction – use of recycled concrete aggregate (Ed.R.K.Dhir), Thomas Telford, London, ISBN 0 7277 2726 5 (1998) pp.189-196

[4] Jacobsen S.: Recycled and porous aggregate in wet frost testing, Proceedings 3rd Nordic Research Seminar in Lund 1999, "Frost resistance of building materials" Div. of Building Materials Lund Inst. of Technology, Sweden, Report TVBM-3087 (1999) pp.69-74

APPENDIX 1

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TEST PROGRAM

Aggregate	Laboratory and test procedure			
	NBI	RB	VTT	SP
LWA	D1 W D1 S D2 W D2 S D3 W D3 S		D1 W D2 W D3 W	D1 S D2 S D3 S
RCA1	D1 W D1 S D2 W D2 S D3 W D3 S		D1 W D2 W D3 W	D1 S D2 S D3 S
NAT1		D1 W D1 S D2 W D2 S D3 W D3 S	D1 S D2 S D3 S	D1 W D2 W D3 W
NAT2		D1 W D1 S D2 W D2 S D3 W D3 S	D1 S D2 S D3 S	D1 W D2 W D3 W

D1 – Aggregates predryed at 105°C before saturation and freeze / thaw cycling
D2 – Aggregates predryed at 40°C before saturation and freeze / thaw cycling
D3 – Aggregates without predrying before saturation and freeze / thaw cycling

W – Deionized water
S – 1% NaCl

APPENDIX 2

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TEST PROCEDURE

Nordtest 1440-99 Freeze/thaw test procedure

1) The test material <8 mm and >16 mm is removed by sieving. Adherent particles are removed by washing.

2) Test specimens are portioned sufficiently according to table 1 below. For each test variable (aggregate, test liquid and pre-drying) 3 parallel specimens are made.

Aggregate size [mm] (sieve away over/undersize if necessary)	Mass of aggregate in specimen (± 0,2 g) (D1: 24h 105 °C, D2: 24h 40 °C, D3: not dried, soaked 24 h, surface dry)			
	LWA	RCA	NAT1	NAT2
8-16	300 g	2000 g	2000 g	1000 g

Table 1: Portioning of test specimens

3) *D1 – procedure*:

3.1.1 Soak all specimens in demineralized water for 24 h

3.1.2 Determine soaked, surface dry weight ($m_{i,\,soaked}$) and volume (V) for **one** specimen (see enclosed worksheet) using wire basket (dry material by hand and paper towel until colour changes from dark to light)

3.1.3 Dry all specimens at 105 °C for 24 h

3.1.4 Measure dry weight ($m_{105\,dry}$) for each specimen (*the mass should correspond to that described in table 1 ± 0,2 g*) and determine water absorption ($abs._{105}$) and dry density (D_{dry}) for one specimen (use worksheet)

3.1.5 Soak all specimens for 24 h in demineralized water (D1W-specimens) and 1 % NaCl (D1S-specimens)

D2 – procedure:

3.1.1 Soak all specimens in water for 24 h

3.1.2 Determine soaked, surface dry weight ($m_{i,\,soaked}$) for **one** specimen (see enclosed worksheet) using wire basket (dry material by hand and paper towel until colour changes from dark to light and)

3.1.3 Dry all specimens at 40 °C for 24 h

3.1.4 Measure dry weight ($m_{40\,dry}$) for each specimen (*the mass should correspond to that described in table 1 ± 0,2 g*) and determine water absorption ($abs._{40}$) for one specimen (use worksheet)

3.1.5 Soak all specimens for 24 h in demineralized water (D2W-specimens) and 1 % NaCl (D2S-specimens)

D3 – procedure:

3.3.1 Soak all specimens in demineralized water (D3W-specimens) or 1 % NaCl (D3S-specimens) for 24 h (without any pre-drying).

3.3.2 Dry all specimens by hand and paper towel until colour changes from dark to light

3.3.3 Measure soaked surface dry mass of all specimens ($m_{soaked,sufacedry}$) (*the mass should correspond to that described in table 1 ± 0,2 g*)

4) Perform 10 freeze-thaw cycles according to the freeze/thaw curve given in prEN 1367-1:1997. However, freezing and thawing is performed in the air-cooled cabinet as described in NT 1214-95. To prevent the LWA aggregate from floating during freeze/thawing, a wire-lid (wire width<8 mm) with a lead (metal, stone, etc.) on top of the aggregate can be used.

5) After completing the 10th cycle, pour the contents of each can into a test sieve of 4 mm aperture size. Wash and sieve the test portion on the specified sieve by hand.

6) Dry all material at 105 °C to constant mass, cool to ambient temperature and weigh both the aggregates larger than 4 mm ($m_{a>4mm}$) immediately after. Determine all necessary results by filling the obtained data into the attached worksheet.

Formulas used in worksheet:

- Dry density:

  - $$D_{dry} = \frac{m_{105}}{V}$$

- Water absorption:

  - $$abs._{105} = \frac{m_{soaked,24h} - m_{105}}{m_{105}}$$

  - $$abs._{40} = \frac{m_{soaked,24h} - m_{40}}{m_{40}}$$

- Frost deterioration F:

  - $$F_{D1} = (1 - \frac{m_{residue,105dry}}{m_{105dry}}) \cdot 100\%$$

  - $$F_{D2} = (1 - \frac{m_{residue,105dry}}{m_{40dry} \cdot (\frac{1 + abs._{40}}{1 + abs._{105}})}) \cdot 100\%$$

  - $$F_{D3} = (1 - \frac{m_{residue,105dry}}{m_{soaked,surfacedry} \cdot (\frac{1}{1 + abs._{105}})}) \cdot 100\%$$

APPENDIX 3

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TEST RESULTS

Symbols:

$m_{i,\ soaked}$ = mass of aggregates after soaking, surface dried
$m_{40\ dry}$ = mass of aggregates dried at 40° for 24h
$m_{105\ dry}$ = mass of aggregates dried at 105° for 24h
$m_{i,\ 105}$ = mass of aggregates dried at 105° for 24h (D1-two times, D2-both 105° and 40°, D3-one time 105°)
V = volume of aggregates
D_{dry} = dry particle density
$Abs._{40}$ = water absorption of aggregates after 24h soaking and 40°C drying
$Abs._{105}$ = water absorption of aggregates after 24h soaking and 105°C drying
$m_{a>4mm}$ = mass of aggregates larger than 4 mm
$m_{a<4mm}$ = mass of aggregates smaller than 4 mm
F_0 = frost damage (calculation, see section 2.2)
F_t = frost damage (calculation, see section 2.2)
$Stdv_o$ = standard deviation
Var_o = varians

Lab.	spec. Nr	test variables									Measurements and calculations											
		Aggregates				Pre-drying			Liquid		$m_{i, soaked}$	$m_{40\ dry}$	V	$m_{105\ dry}$	D_{dry}	$Abs._{40}$	$Abs._{105}$	$m_{a>4mm}$	F_o	$F_{average}$	$Stdv_o$	Var_o
		LWA	RCA	NAT1	NAT2	D1	D2	D3	W	S	[g]	[g]	[cm³]	[g]	[kg/m³]	[-]	[-]	[g]	[%]	[%]	[-]	[-]
NBI	1	x				x			x		306		536,6	300,1	559,3		0,096	286	4,7			
	2	x				x			x					300,2				290,4	3,3			
	3	x				x			x					300				289,1	3,6	3,9	0,74	0,55
	4	x				x				x	307		545,9	300	549,6		0,094	293,8	2,1			
	5	x				x				x				300,1				296,1	1,3			
	6	x				x				x				300,2				300,1	0	1,1	1,03	1,06
	7	x					x		x		330	300,2				0,096		289	3,7			
	8	x					x		x			300						289,2	3,6			
	9	x					x		x			300,2						290,5	3,2	3,5	0,26	0,07
	10	x					x			x	332	299,9				0,095		294,9	1,8			
	11	x					x			x		299,8						291,5	2,9			
	12	x					x			x		300,1						298,7	0,6	1,7	1,15	1,32
	13	x						x	x		299,9							254,5	7			
	14	x						x	x		299,9							249,2	8,9			
	15	x						x	x		300,2							246,2	10	8,7	1,58	2,49
	16	x						x		x	296,1							263,7	2,6			
	17	x						x		x	290,3							261	1,6			
	18	x						x		x	291,5							261,6	1,8	2,0	0,49	0,24
	19		x			x			x		2169,5		931,2	1999,9	2148		0,076	1878,3	6,1			
	20		x			x			x					1999,9				1843	7,9			
	21		x			x			x					2000,1				1818	9,1	7,7	1,51	2,29
	22		x			x				x	2224,0		943,6	1999,9	2119		0,064	1474	26			
	23		x			x				x				2000,0				1529	24			
	24		x			x				x				1999,9				1473	26	25,4	1,6	2,57

Lab.	spec. Nr	test variables									Measurements and calculations											
		Aggregates				Pre-drying			Liquid		soaked,surfac	$m_{40\ dry}$	V	$m_{105\ dry}$	D_{dry}	$Abs._{40}$	$Abs._{105}$	$m_{a>4mm}$	F_o	F_t	$Stdv_o$	Var_o.
		LWA	RCA	NAT1	NAT2	D1	D2	D3	W	S	[g]	[g]	[m^3]	[g]	[kg/m^3]	[-]	[-]	[g]	[%]	[%]	[-]	[-]
NBI	25		x				x		x		2572,6	2000,0				0,027		1853	3			
	26		x				x		x			1999,8						1841	3,5			
	27		x				x		x			2000,2						1791	6,2	4,2	1,72	2,97
	28		x				x			x	2427,2	1999,8				0,032		1580	19			
	29		x				x			x		2000,2						1576	19			
	30		x				x			x		2000,0						1576	19	18,7	0,13	0,02
	31		x					x	x		1999,8							1745	6,1			
	32		x					x	x		1999,8							1851	0,4			
	33		x					x	x		2000,1							1845	0,8	2,4	3,19	10,2
	34		x					x		x	2000,2							1528	19			
	35		x					x		x	2000,3							1564	17			
	36		x					x		x	2000,3							1520	19	18,2	1,23	1,52

Lab.	spec. Nr.	test variables									Measurements and calculations																
		Aggregates				Pre-drying			Liquid		$m_{i, soaked}$	$m_{40\ dry}$	V	$m_{105\ dry}$	D_{dry}	$Abs._{40}$	$Abs._{105}$	$m_{a<4mm}$	$m_{a>4mm}$	F_o	$F_{o(a)}$	F_t	$F_{t(a)}$	$Stdv_o$	Var_o	$Stdv_t$	Var_t
		LWA	RCA	NAT1	NAT2	D1	D2	D3	W	S	[g]	[g]	[cm³]	[g]	kg/m³	[-]	[-]	[g]	[g]	[%]	[%]	[%]	[%]	[-]	[-]	[-]	[-]
RB	1			x		x			x		1308		428	1233,5	2884		0,06	5,8	1228	0,5		0,5					
	2			x		x			x					1272,1				4,8	1267	0,4		0,4					
	3			x		x			x					1235,0				4,7	1230	0,4	0,4	0,4	0,4	0,1	0	0,1	0
	4			x		x				x	1308		428	1226,0	2866		0,066	19,6	1206	1,6		1,6					
	5			x		x				x				1241,4				32,4	1209	2,6		2,6					
	6			x		x				x				1265,8				25,2	1241	2	2,1	2	2,1	0,5	0,26	0,5	0,3
	7			x			x		x		1827	1734,5				0,05		-1,1	1267	26		-0,1					
	8			x			x		x			1219,3						-3,6	1194	1,4		-0,3					
	9			x			x		x			1221,9						5,2	1216	-0,1	9,3	0,4	0,0	15	223	0,4	0,1
	10			x			x			x	1827	1734,5				0,05		39,5	1138	34		3,4					
	11			x			x			x		1116,8						27,3	1068	3,1		2,5					
	12			x			x			x		1189,7						18,5	1158	1,5	12,7	1,6	2,5	18	327	0,9	0,8
	13			x				x	x		1268							3,9	1187	0,8		0,3					
	14			x				x	x		1309							5,5	1222	1,1		0,4					
	15			x				x	x		1210							6,2	1128	1,1	1,0	0,5	0,4	0,2	0,03	0,1	0
	16			x				x		x	1256							2,6	1173	0,4		0,2					
	17			x				x		x	1293							7,7	1208	0,4		0,6					
	18			x				x		x	1303							10,8	1217	0,4	0,4	0,9	0,6	0	0	0,3	0,1
	19				x	x			x		611,6		597	284,0	476		1,154	29,9	249,2	12		11					
	20				x	x			x					269,5				6,2	263,3	2,3		2,3					
	21				x	x			x					287,1				23,5	263,3	8,3	7,6	8,2	7,1	5	25,1	4,3	19
	22				x	x				x	611,6		597	284,0	476		1,154	-1,5	270,1	4,9		-0,6					
	23				x	x				x				284,0				-1,8	285,8	-0,6		-0,6					
	24				x	x				x				281,5				-1,2	282,7	-0,4	1,3	-0,4	-0,5	3,1	9,82	0,1	0

Lab.	spec. Nr	test variables									Measurements and calculations																
		Aggregates				Pre-drying			Liquid		$m_{soaked,surfa}$	$m_{40\ dry}$	V	$m_{105\ dry}$	D_{dry}	$Abs._{40}$	$Abs._{105}$	$m_{a<4mm}$	$m_{a>4mm}$	F_o	$F_{o(a)}$	F_t	$F_{t(a)}$	$Stdv_o$	Var_o	$Stdv_o$	Var_o
		LWA	RCA	NAT1	NAT2	D1	D2	D3	W	S	[g]	[g]	$[m^3]$	[g]	$[kg/m^3]$	[-]	[-]	[g]	[g]	[%]	[%]	[%]	[%]	[-]	[-]	[-]	[-]
RB	25				x		x		x		868,3	523,1				0,2		114,1	146,6	50		44					
	26				x		x		x			500,2						61,3	219,9	21		22					
	27				x		x		x			535,6						87,5	183,5	39	36,4	32	32,6	14	208	14	208
	28				x		x			x	868,3	422				0,2		-23,2	263,0	-12		-9,7					
	29				x		x			x		503,8						-3,4	264,6	5,7		-1,3					
	30				x		x			x		470,3						-7,5	262,4	-0,1	-2,1	-2,9	-4,6	9	80,2	9	80
	31				x			x	x		597,4							54,8	218,8	80,2		20					
	32				x			x	x		611,5							74,5	215,9	73,8		26					
	33				x			x	x		580,1							49,5	217,1	81,6	78,5	19	21,4	4,2	17,6	4,2	18
	34				x			x		x	645,0							30,5	279,4	89,8		9,8					
	35				x			x		x	594,5							24,3	256,6	91,2		8,7					
	36				x			x		x	585,1							15,8	259,4	94,2	91,7	5,7	8,1	2,2	4,98	2,2	5

Lab.	spec. Nr.	test variables									Measurements and calculations																		
		Aggregates				Pre-drying			Liquid		$m_{i,\,sat}$	$m_{i,\,105}$	$m_{40\,dry}$	$m_{i,\,105}$	V	$m_{105\,dry}$	$m_{i,\,105}$	D_{dry}	$Abs._{40}$	$Abs._{10}$	$m_{a<4mm}$	$m_{a>4mm}$	F_o	$F_{o(a)}$	F_t	$F_{t(a)}$	Var_o	$Stdv_t$	Var_t
		LWA	RCA	NAT1	NAT2	D1	D2	D3	W	S	[g]	[g]	[g]	[g]	[cm^3]	[g]	[g]	[kg/m^3]	[-]	[-]	[g]	[g]	[%]	[%]	[%]	[%]	[-]	[-]	[-]
SP	4	x				x				x	334				606	300	300,3	495		0,11	0,6	300	0,03	0,0	0,2	0,3	0,0	0,1	0,0
	5	x				x				x						300,2	300,3				1,2	301	-0,1		0,4				
	6	x				x				x						300	300,2				0,6	300	0		0,2				
	1			x		x			x		2056				827	1996	2000,1	2415		0,03	4,7	1992	0,42	0,4	0,24	0,2	0,0	0,0	0,0
	2			x		x			x							1998	2000,5				5,5	1992	0,42		0,28				
	3			x		x			x							1997	2000				4,2	1994	0,32		0,21				
	10	x					x			x	342		311,4	300,1					0,099		0,58	300	0,04	-0,1	0,19	0,2	0,0	0,0	0,0
	11	x					x			x			320,4	300							0,44	300	-0,1		0,15				
	12	x					x			x			326,8	300,1							0,37	300	-0,1		0,12				
	7			x			x		x		2064		2023	2000					0,02		9,93	1987	0,68	0,4	0,5	0,3	0,0	0,2	0,0
	8			x			x		x				2090	2000							4,68	1993	0,34		0,23				
	9			x			x		x				2080	2000							4,44	1994	0,31		0,22				
	16	x						x		x	339	300,1									0,4	300	-0	-0,1	0,13	0,2	0,0	0,1	0,0
	17	x						x		x	340	300,1									0,6	301	-0,1		0,2				
	18	x						x		x	338	300,2									0,8	300	-0,1		0,27				
	13			x				x	x		2062	2000									3,5	1994	0,28	0,3	0,18	0,2	0,0	0,0	0,0
	14			x				x	x		2060	2000									3,6	1994	0,31		0,18				
	15			x				x	x		2062	2000									4,6	1992	0,38		0,23				
	22		x			x				x	2072				876	1948	1961,1	2224		0,06	498	1455	25,8	27,3	25,5	26,8	1,9	1,3	1,6
	23		x			x				x						1958	1963,5				522	1424	27,5		26,8				
	24		x			x				x						1955	1968,3				549	1406	28,6		28,1				
	19				x	x			x		527				580	314	315,1	541,4		0,68	25,9	286	9,14	7,7	8,3	6,8	13,7	3,8	14,5
	20				x	x			x							313,4	315,2				7,6	304	3,46		2,44				
	21				x	x			x							314,4	315,2				29,9	282	10,4		9,57				

Lab.	sp	test variables									Measurements and calculations																			
		Aggregates				Pre-drying			Liquid		$m_{i, sat}$	$m_{i, 105}$	$m_{40\ dry}$	$m_{i, 105}$	V	$m_{105\ dry}$	$m_{i, 105}$	D_{dry}	$Abs._{40}$	$Abs._{10}$	$m_{a<4mm}$	$m_{a>4mm}$	F_o	$F_{o(a)}$	F_t	$F._{o(a)}$	Var_o.	$Stdv_t$.	Var_t.
		LWA	RCA	NAT1	NAT2	D1	D2	D3	W	S	[g]	[g]	[g]	[g]	[m³]	[g]	[g]	[kg/m³]	[-]	[-]	[g]	[g]	[%]		[%]		[-]	[-]	[-]
SP	28		x				x			x	2088		2023	1978					0,032		494	1462	26,1	25,8	25,3	25,2	0,6	0,6	0,4
	29		x				x			x			2078	1970							505	1450	26,4		25,8				
	30		x				x			x			2063	1964							479	1474	24,9		24,5				
	25				x		x		x		521		470,9	315,1					0,106		7,16	303	3,89	7,2	2,31	5,6	22,3	5,1	26
	26				x		x		x				499,9	315,1							35,7	276	12,6		11,5				
	27				x		x		x				510,4	314,9							9,24	299	5		3				
	34		x					x		x	2078	1962									471	1478	24,7	25,0	24,2	24,4	1,85	1,2	1,5
	35		x					x		x	2075	1962									454	1496	23,7		23,3				
	36		x					x		x	2072	1960									498	1442	26,4		25,7				
	31				x			x	x		505	314,9									5,7	294	6,67	4,0	1,9	1,7	5,47	0,2	0
	32				x			x	x		527	315,1									5	307	2,67		1,6				
	33				x			x	x		536	315,2									4,7	307	2,57		1,51				

Lab.	spec. Nr.	test variables									Measurements and calculations (NBI, RB, VTT and SP)																
		Aggregates				Pre-drying			Liquid		$m_{i, sat}$	$m_{40\ dry}$	V	$m_{105\ dry}$	D_{dry}	$Abs._{40}$	$Abs._{105}$	$m_{a<4mm}$	$m_{a>4mm}$	F_o	$F_{o, a}$	F_t	$F_{t, a}$	$Stdv_o$	Var_o	$Stdv_t$	Var_t
		LWA	RCA	NAT1	NAT2	D1	D2	D3	W	S	[g]	[g]	[m^3]	[g]	[kg/m^3]	[-]	[-]	[g]	[g]	[%]	[%]	[%]	[%]	[-]	[-]	[-]	[-]
VTT	1	x				x			x				0,066	300	477,3		0,123		275	8,33							
	2	x				x			x					300					256	14,7							
	3	x				x			x					300					284	5,33	9,44			4,76	22,7		
	4			x		x				x			0,844	2000	2437		0,065	66	1923	3,85		3,32					
	5			x		x				x				2000				60	1923	3,85		3,03					
	6			x		x				x				2000				75	1909	4,55	4,08	3,78	3,37	0,4	0,2	0,38	0,14
	7	x					x		x			300				0,123			283	5,67							
	8	x					x		x			300							293	2,33							
	9	x					x		x			300							293	2,33	3,44			1,92	3,7		
	10			x			x			x		2000				0,062		64	1909	4,28		3,24					
	11			x			x			x		2000						66	1912	4,13		3,34					
	12			x			x			x		2000						60	1913	4,08	4,16	3,04	3,21	0,1	0,0	0,15	0,02
	13	x						x	x		300								233	12,8							
	14	x						x	x		300								248	7,17							
	15	x						x	x		300								252	5,67	8,54			3,75	14,1		
	16			x				x		x	1886							92	1602	9,54		5,43					
	17			x				x		x	1915							73	1683	6,4		4,16					
	18			x				x		x	1920							82	1668	7,48	7,81	4,69	4,76	1,59	2,5	0,64	0,41
	19		x			x			x				1,284	2000	1621		0,076		1853	7,35							
	20		x			x			x					2000					1862	6,9							
	21		x			x			x					2000					1855	7,25	7,17			0,24	0,1		
	22				x	x				x	562		0,496	257	518,1		1,187	1	313	-22		0,32					
	23				x	x				x				260				1	337	-30		0,3					
	24				x	x				x				257				1	309	-20	-24	0,32	0,31	5,03	25,3	0,01	0

Lab.	sp	test variables									Measurements and calculations (NBI, RB, VTT and SP)																
		Aggregates				Pre-drying			Liquid		$m_{i,\,sat}$	$m_{40\,dry}$	V	$m_{105\,dry}$	D_{dry}	$Abs._{40}$	$Abs._{105}$	$m_{a<4mm}$	$m_{a>4mm}$	F_o		F_t		$Stdv_o$	Var_o	$Stdv_t$	Var_t
		LWA	RCA	NAT1	NAT2	D1	D2	D3	W	S	[g]	[g]	[m³]	[g]	[kg/m³]	[-]	[-]	[g]	[g]	[%]		[%]		[-]	[-]	[-]	[-]
VTT	25		x				x		x			2000				0,027			1849	3,14							
	26		x				x		x			2000							1824	4,45							
	27		x				x		x			2000							1812	5,08	4,22			0,99	1,0		
	28				x		x			x		453				0,216		21	347	-38		5,71					
	29				x		x			x		460						20	346	-35		5,46					
	30				x		x			x		433						16	337	-40	-38	4,53	5,23	2,35	5,5	0,62	0,38
	31		x					x	x		1999								1787	3,81							
	32		x					x	x		1995								1767	4,7							
	33		x					x	x		2000								1812	2,51	3,67			1,1	1,2		
	34				x			x		x	551							43	313	-24		12,1					
	35				x			x		x	552							39	294	-16		11,7					
	36				x			x		x	544							37	368	-48	-30	9,14	11	16,4	268,7	1,6	2,57