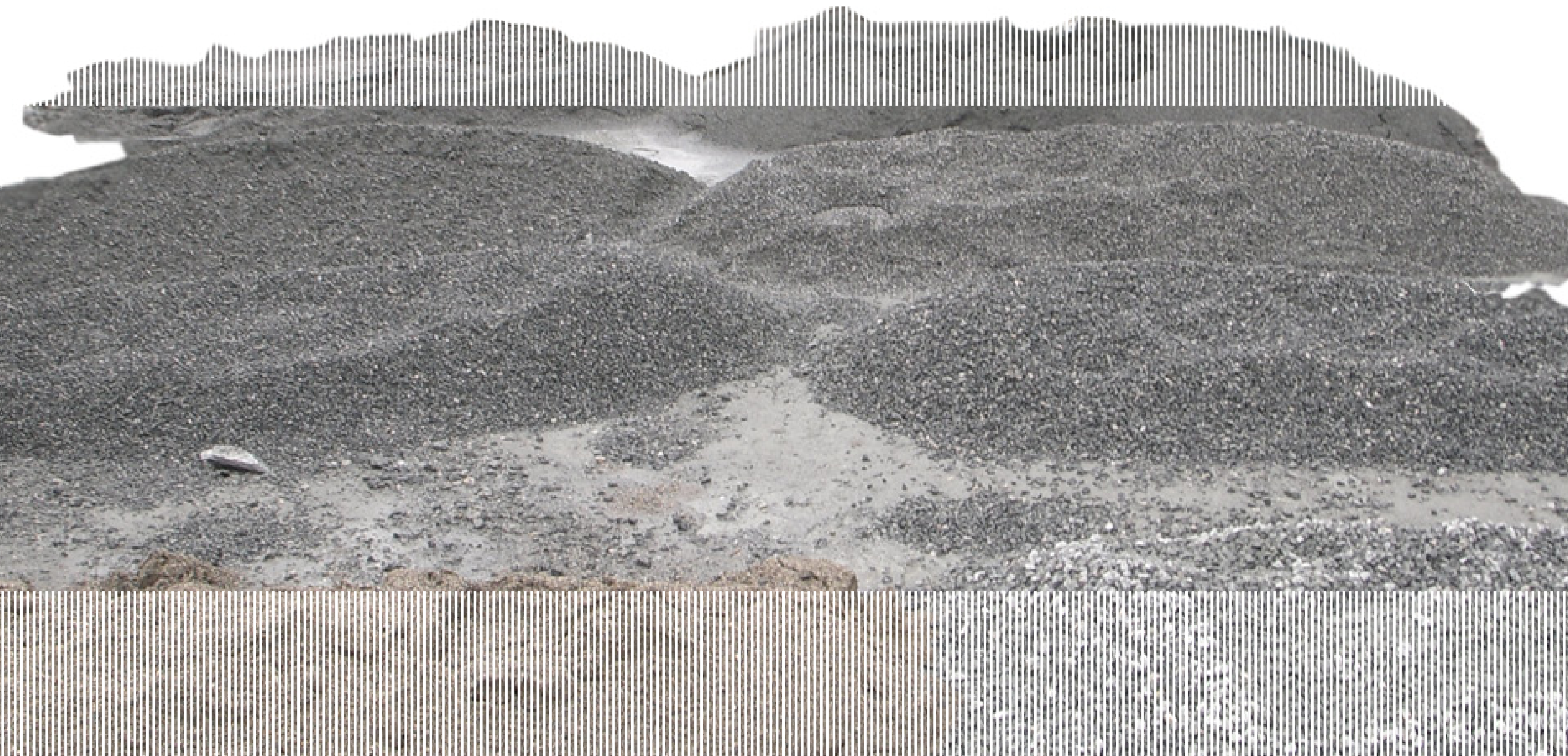
www.coinweb.no

SINTEF Building and Infrastructure Rolands Cepuritis (Norsk Stein AS)

A preliminary study on using manufactured sand from Jelsa Quarry for the production of plastic concrete mixes

COIN Project report 42 – 2012



SINTEF Building and Infrastructure

Rolands Cepuritis (Norsk Stein AS)

A preliminary study on using manufactured sand from Jelsa Quarry for the production of plastic concrete mixes

FA 2 Competitive constructions

SP 2.1 High quality manufactured sand for concrete

COIN Project report 42 – 2012

COIN Project report no 42
Rolands Cepuritis (Norsk Stein AS)

A preliminary study on using manufactured sand from Jelsa Quarry for the production of plastic concrete mixes

FA 2 Competitive constructions
SP 2.3 High quality manufactured sand for concrete

Keywords:
Manufactured sand; fresh concrete; case study; self-compacting concrete

Project no.: 3D005940

Photo, cover: Rolands Cepuritis

ISSN 1891–1978 (online)
ISBN 978-82-536-1291-1 (pdf)
ISBN 978-82-536-1292-8 (printed)

13 copies printed by AIT AS e-dit
Content: 100 g Scandia
Cover: 240 g Trucard

Address: Forskningsveien 3 B
POBox 124 Blindern
N-0314 OSLO
Tel: +47 22 96 55 55
Fax: +47 22 69 94 38 and 22 96 55 08

www.sintef.no/byggforsk
www.coinweb.no

Cooperation partners / Consortium Concrete Innovation Centre (COIN)

Aker Solutions
Contact: Jan-Diederik Advocaat
Email: jan-diederik.advocaat@akersolutions.com
Tel: +47 67595050

Saint Gobain Weber
Contact: Geir Norden
Email: geir.norden@saint-gobain.com
Tel: +47 22887700

Norcem AS
Contact: Terje Rønning
Email: terje.ronning@norcem.no
Tel: +47 35572000

NTNU
Contact: Terje Kanstad
Email: terje.kanstad@ntnu.no
Tel: +47 73594700

Mapei AS
Contact: Trond Hagerud
Email: trond.hagerud@mapei.no
Tel: +47 69972000

SINTEF Building and Infrastructure
Contact: Tor Arne Hammer
Email: tor.hammer@sintef.no
Tel: +47 73596856

Skanska Norge AS
Contact: Sverre Smeplass
Email: sverre.smeplass@skanska.no
Tel: +47 40013660

Norwegian Public Roads Administration
Contact: Kjersti K. Dunham
Email: kjersti.kvalheim.dunham@vegvesen.no
Tel: +47 22073940

Unicon AS
Contact: Stein Tosterud
Email: stto@unicon.no
Tel: +47 22309035

Veidekke Entreprenør ASA
Contact: Christine Hauck
Email: christine.hauck@veidekke.no
Tel: +47 21055000

Preface

This study has been carried out within COIN - Concrete Innovation Centre - one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfil this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %).

For more information, see www.coinweb.no

Tor Arne Hammer
Centre Manager

TABLE OF CONTENTS

1. INTRODUCTION

From 2008 to 03/2010 (start of the study) the concrete produced in a mobile plant in Jelsa quarry for an upgrade/ expansion construction project demands was made using natural 0/8 mm sand from and outsource combined with a local granodiorite crushed material (D_{max} of 16 mm). Back in 1993 for another construction project within Norsk Stein a usable concrete had been produced using only crushed material from the same rock type and production lines. In October 2009 a preliminary testing of 100% crushed mix design had been carried out in the full-scale production of the new mobile concrete plant but it had been a failure – total separation of the mix.

Therefore the main aim of this study was to find a way (an approach to the mix design) how to produce concrete on 100% local crushed material satisfying the same demands (pumpability and workability) as the concrete being used for the construction project so far. To gain an economical benefit from the study new mixes should have been with a lower concrete self-price as the ones made with the natural sand.

In total 42 laboratory tests were completed to find a mix composition (grading and matrix volume l/m^3) providing the lowest water demand while still producing a normal vibrated structural concrete according to the demand from the project.

This report contains information about the reference concrete from 0/8 mm natural sand, used approach for the laboratory tests and a summary of all the test results.

2. REFERENCE CONCRETE

Two types of concrete had been mainly used for the construction project until the start of the study - structural concrete with a compressive strength class C30/37 (B30) and lean concrete with a compressive strength class C10/12 (B10). Both of the mixes were pumpable and the desired workability varied from S3 to S5 (approximately a slump of 150 to 230 mm). The consistency of the concrete was changed by adjusting the water content of the mix to the necessary level (leaving everything else invariable).

Natural sand 0/8 mm (naturally rounded glaciofluvial aggregate; see figures 2-1 and 2-2) in a combination with crushed material from Jelsa quarry in fractions 0/2 (normal washed), 8/11 and 11/16 mm were used for the concrete production.

Figure 2-1 Naturally rounded glaciofluvial aggregate 0/8 mm used for concrete production in a mobile concrete plant in Jelsa quarry

CEM I 42.5R (STD) from Norcem AS was used as the binder together with a high range water reducing, superplasticising admixture Dynamon SX-N (acrylic polymers based, solids content 18.5%) from ResconMapei AS.

Table 2-1 and figure 2-3 contain the mix design of C30/37 concrete made with natural sand 0/8 mm.

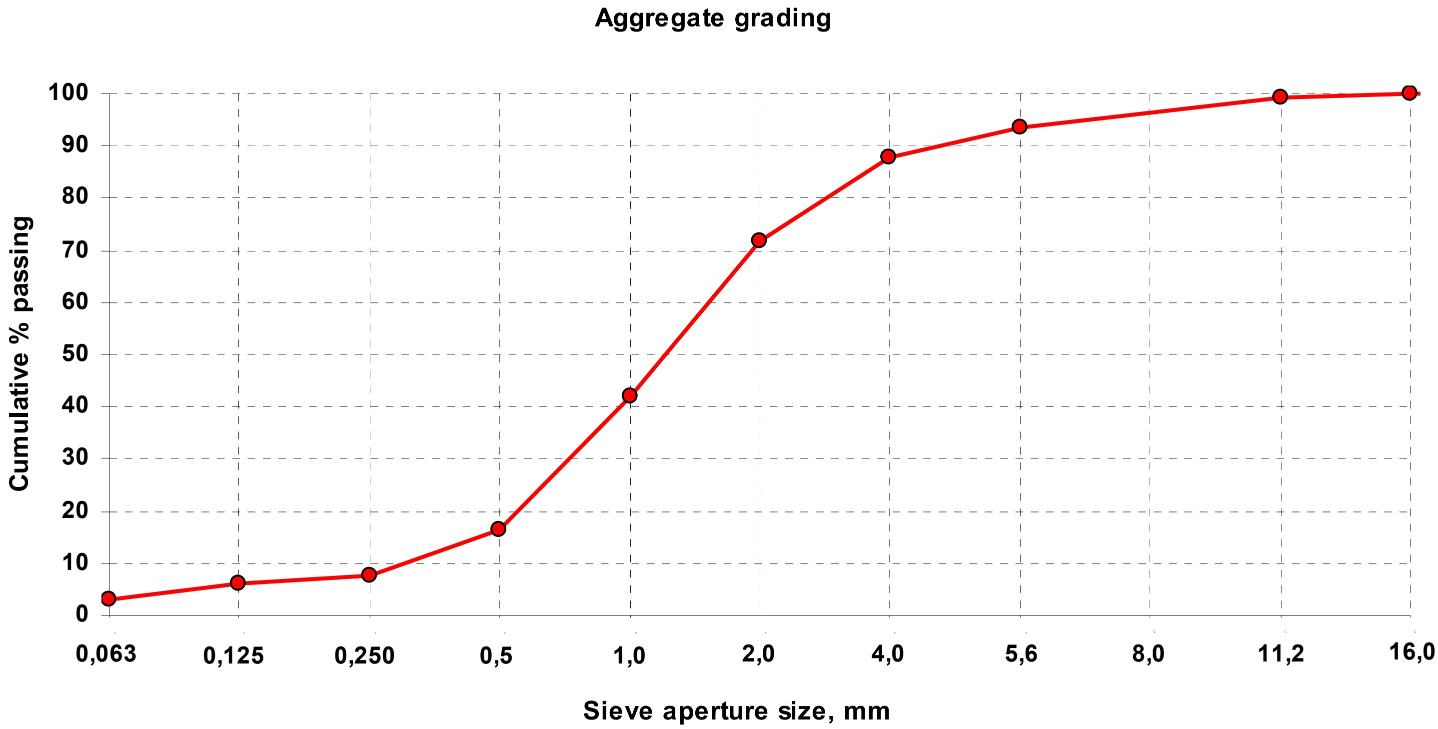


Figure 2-2 Grading curve of the naturally rounded glaciofluvial aggregate 0/8 mm used for concrete production in a mobile plant in Jelsa quarry (**FM=3.69**; FM was calculated from cumulative material retaining on the standard sieve set according to *NS EN 12620*).

Table 2-1

Mix Design of C30/37 Concrete Made With Natural Sand 0/8 mm*

Natural sand 0/8, kg/m^3; **(%)**	965.5 **(5)**
Jelsa 0/2 (normal washed), kg/m^3; **(%)**	89.9 **(53)**
Jelsa 8/11, kg/m^3; **(%)**	305.2 **(17)**
Jelsa 11/16, kg/m^3; **(%)**	457.6 **(25)**
CEM I 42.5R (STD), kg/m^3	**380**
Water, kg/m^3	191.5
Dynamon SX-N, kg/m^3 **(m% from cement)**	1.8 **(0.47)**
w/c	0.504
Matrix volume, l/m^3	**341**
Slump, mm	**210**
Compressive strength at 28 days $f_{c,cube}$, MPa	**54.0**

***Recalculated so that the volume of the mix design would be exactly 1 m^3**

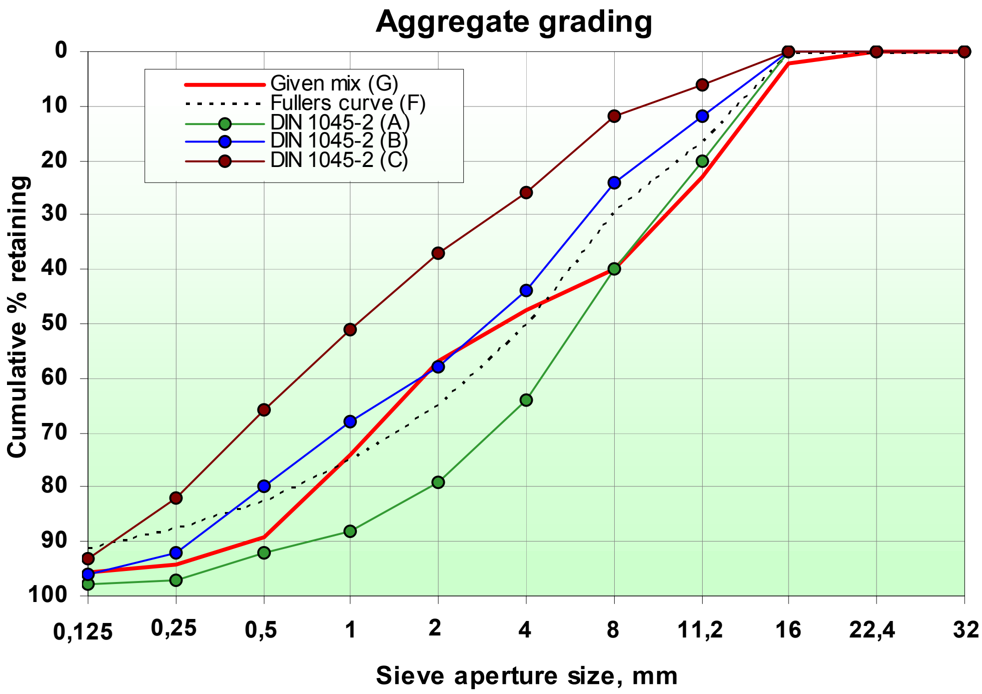


Figure 2-3 Aggregate grading curve of C30/37 concrete made with natural sand 0/8 mm

Lean concrete with the compressive strength class C10/12 (B10) was produced using the same mix composition as for C30/37 concrete (see table 2-1) by reducing the cement content to 280 kg/m^3. Everything else was left invariable. An additional demand for this type concrete was that if the lean concrete layer had been casted in the evening it should already be “hard enough” until the morning of the next day. No compressive strength tests had been performed for lean concrete.

3. LABORATORY TESTS AND RESULTS

3.1 Aggregates

Only 100% crushed granodiorite material from Jelsa quarry was used for the laboratory tests. See figure 3-1 for the grading curves of the aggregates.

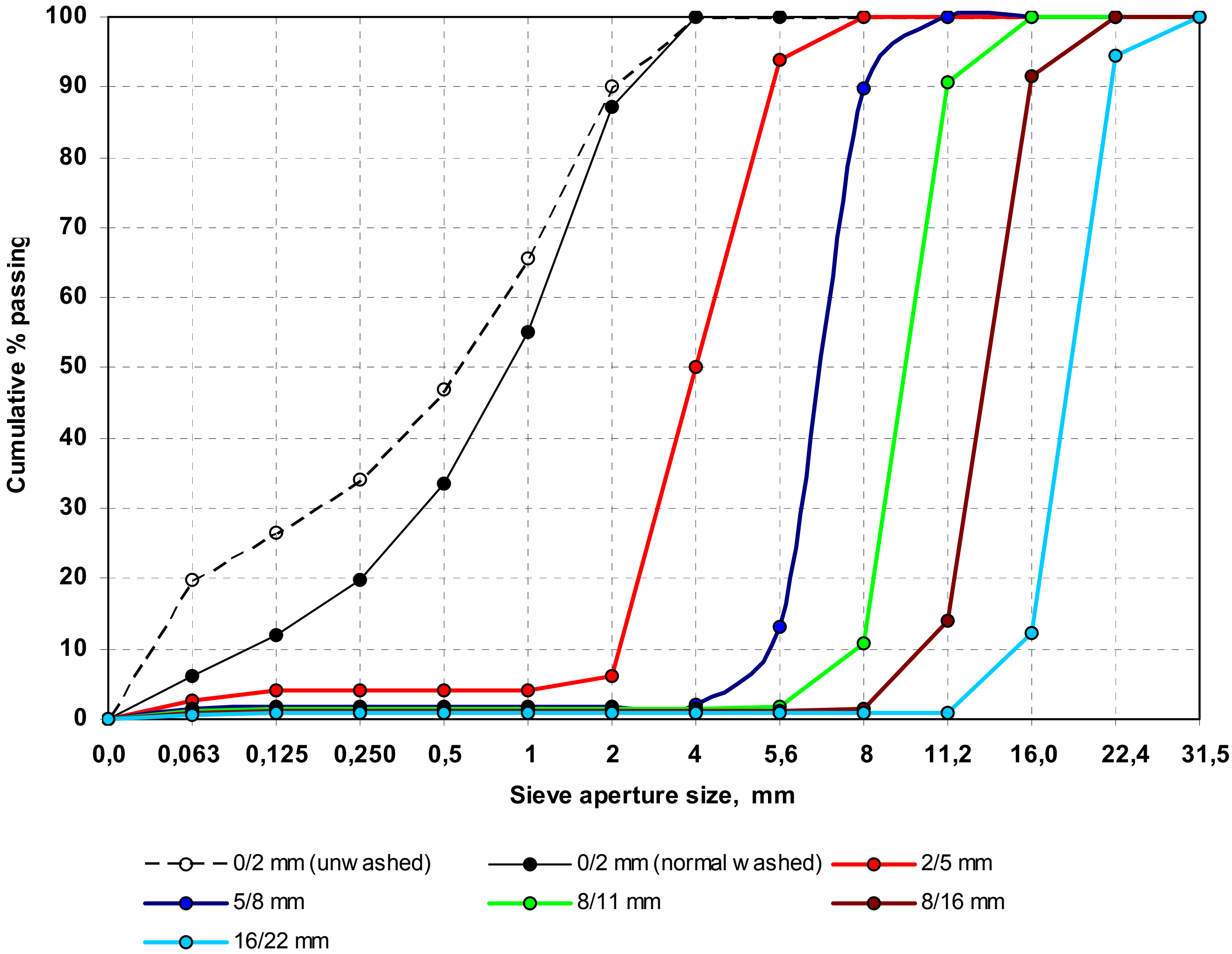


Figure 3-1 Grading curves of the crushed material used for the laboratory tests

The material had been produced in three steps of crushing. Cone crushers GP550 from Metso Minerals were used for the last step.

Granodiorite rock in Jelsa deposit is rather hard with a Los Angeles value of 15 (test fraction 10/14 mm), Micro Deval value of 7 (test fraction 10/14 mm) and a water absorption of only 0.4% (test fraction 8/11 mm).

The flakiness index for the fraction 8/11 mm is 11 and preliminary tests in mortars showed low water demand properties when these aggregates were compared to crushed material from other sources.

3.2 Test Methods

All the laboratory mixes were prepared in a regular free-fall mixer with a maximum nominal batch size of 50 l (figure 3-2).

A constant mixing procedure was used (figure 3-3) to achieve a good repeatability of the tests and to get a correlation as close as possible with the further full-scale results.

Aggregate moisture and water absorption were taken into account when designing and preparing the laboratory mixes.

Figure 3-2 Free-fall mixer that was used to prepare the laboratory concrete mixes

If the laboratory concrete test-mix was plastic enough to measure the workability - it was done in a way described below:

1. The slump and slump-flow of the concrete was measured using the method and slump cone according to *NS EN 12350-2* on a flow-table according to *NS EN 12350-5*;
2. Five dumps according to *NS EN 12350-5* were performed with the flow table and the slump and slump-flow of the mix was measured again. All the results were documented.

For most of the mixes pictures of the slump test before and after the five damps on the flow-table were taken.

1. Desirable concrete mix-design is recalculated for the laboratory batch size (10 litres) taking into account aggregate moisture and water absorption;

2. All the materials are weighted up;

↓

3. Concrete mixer is pre-wetted and left for 1 min with the discharging opening pointed towards the ground to let all the excess water flow away;

4. The coarse fractions (5-22 mm) are added in the mixer together with all of the cement;

5. Mixed for 1 min;

↓

6. Fine fractions (0-5 mm) are added in the mixer;

7. Mixed for 1 min;

↓

8. 90% of the water is added in the mixer;

9. Mixed for 1 min;

↓

10. Admixture mixed together with the left 10% of water is added in the mixer;

11. Mixed for 3 min;

12. The mix is left to rest for 1 min;

13. Mixed for 3 min.

Figure 3-3 Operation order to prepare the manufactured sand concrete in the laboratory mixer

3.3 Repeatability and Batch-volume Effect of the Tests

As quite an excessive testing had to be carried out in a rather short period of time the batch size of the laboratory mixes was reduced to 10 litres. To make sure the reduced batch-size has no negative effect on the repeatability of the tests and the accuracy of determining the water demand, two series of verification tests were completed.

Results of the batch volume effect influence testing are presented in table 3-1, but the results from repeatability testing in table 3-2.

Table 3-1

Influence of the Batch-volume size on the Water Demand of the Mix

Test ID:	Initial mix design	**R1-35**	**R1-34**
Date of testing		24/03/2010	24/03/2010
Batch volume, litres	**1000***	**10****	**20****
Jelsa 0/2 (unwashed), kg	926	10.176	20.352
Jelsa 8/11, kg	463	4.694	9.388
Jelsa 11/16, kg	463	4.654	9.307
CEM I 42.5R (STD), kg	**345**	**3.450**	**6.901**
Water, kg	196.7	1.015	2.029
Dynamon SX-N, kg **(m% from cement)**	2.76 **(0.8)**	0.028 **(0.8)**	0.055 **(0.9)**
Slump, mm		**225**	**225**
Slump-flow, mm		**340**	**330**
Slump (after 5 dumps), mm		**250**	**240**
Slump-flow (after 5 dumps), mm		**410**	**390**

*Mix design for dry material;
**Mix design taking into account real moisture of the material at the moment of testing.

Table 3-2

Repeatability Testing of the Used Method

Test ID:	Initial mix design	**R1-18**	**R1-27**
Date of testing		19/03/2010	24/03/2010
Batch volume, litres	**1000***	**10****	**10****
Jelsa 0/2 (unwashed), kg	883.3	9.727	9.579
Jelsa 5/8	265	2.679	2.695
Jelsa 8/11, kg	265	2.662	2.650
Jelsa 11/16, kg	353.3	3.533	3.533
CEM I 42.5R (STD), kg	**380**	**3.800**	**3.800**
Water, kg	216.6	1.273	1.419
Dynamon SX-N, kg **(m% from cement)**	3.04 **(0.8)**	0.030 **(0.8)**	0.030 **(0.8)**
Slump, mm		**240**	**235**
Slump-flow, mm		**470**	**470**
Slump (after 5 dumps), mm		**250**	**250**
Slump-flow (after 5 dumps), mm		**550**	**530**

*Mix design for dry material;

**Mix design taking into account real moisture of the material at the moment of testing.

From the data presented in tables 3-1 and 3-2 it can be stated that the chosen method for the laboratory tests is of a required repeatability and shows no dependence of the chosen mix batch volume in the range of 10 to 20 litres.

3.4 Testing Program

All the tests carried out can be divided into certain groups depending on the goal to be achieved (see chapters 3.4.1 to 3.4.9). The overall concept of the laboratory tests was finding a certain "starting point" that should be understood as a mix of normal vibrated concrete that could be used for the construction project in the quarry. The next steps completed include a further development of the "starting point" mix to get the self-price of the concrete as low as possible and also to learn more about the effect of using manufactured sand from Jelsa in plastic concrete mixes.

3.4.1 Natural Sand Concrete Approach and the "Starting Point"

To find a "starting point" for the tests it was chosen to begin with the same considerations as for a regular natural sand concrete. At the beginning 10 different mixes (figure 3-4) representing a wide range of gradings around the Fuller's curve at different matrix* volumes (350-442 l/m^3) were tested.

Already the first efforts showed a clear lack in fines/ matrix volume when compared to the natural sand reference concrete. Matrix volume of 350 l/m^3 for the grading R1-2 gave a completely unusable mix that does not form a plastic vibrated concrete (figure 3-5), at matrix volumes from 410 to 424 l/m^3 for the gradings R1-11 (figure 3-6) to R1-13 it was already possible to acquire a homogenous mix but only matrix volume of 442 l/m^3 for grading R1-14 (figure 3-7) formed a plastic vibrated concrete that was hard to be distinguished from the reference natural sand concrete. Mix R1-14 (table 3-3) was chosen as the "starting point" for further testing.

***The matrix phase** of a concrete mix is defined to consist of free water, admixtures and all solid particles having particle size less than 0.125 mm, i.e., cement and the filler of the aggregate. The matrix phase may be regarded as a viscous liquid, and my in principle be characterized as other liquids.*

Table 3-3

Mix Design and Flowability Testing Results for Test R1-14

Test ID:	Initial mix design	**R1-14**
Date of testing		18/03/2010
Batch volume, litres	**1000***	**10****
Jelsa 0/2 (unwashed), kg	858.8	9.305
Jelsa 5/8	257.7	2.604
Jelsa 8/11, kg	257.7	2.579
Jelsa 11/16, kg	343.5	2.435
CEM I 42.5R (STD), kg	**400**	**4.000**
Water, kg	228	1.577
Dynamon SX-N, kg **(m% from cement)**	3.20 **(0.8)**	0.032 **(0.8)**
Slump, mm		**230**
Slump-flow, mm		**410**
Slump (after 5 dumps), mm		**250**
Slump-flow (after 5 dumps), mm		**480**

*Mix design for dry material;

**Mix design taking into account real moisture of the material at the moment of testing.

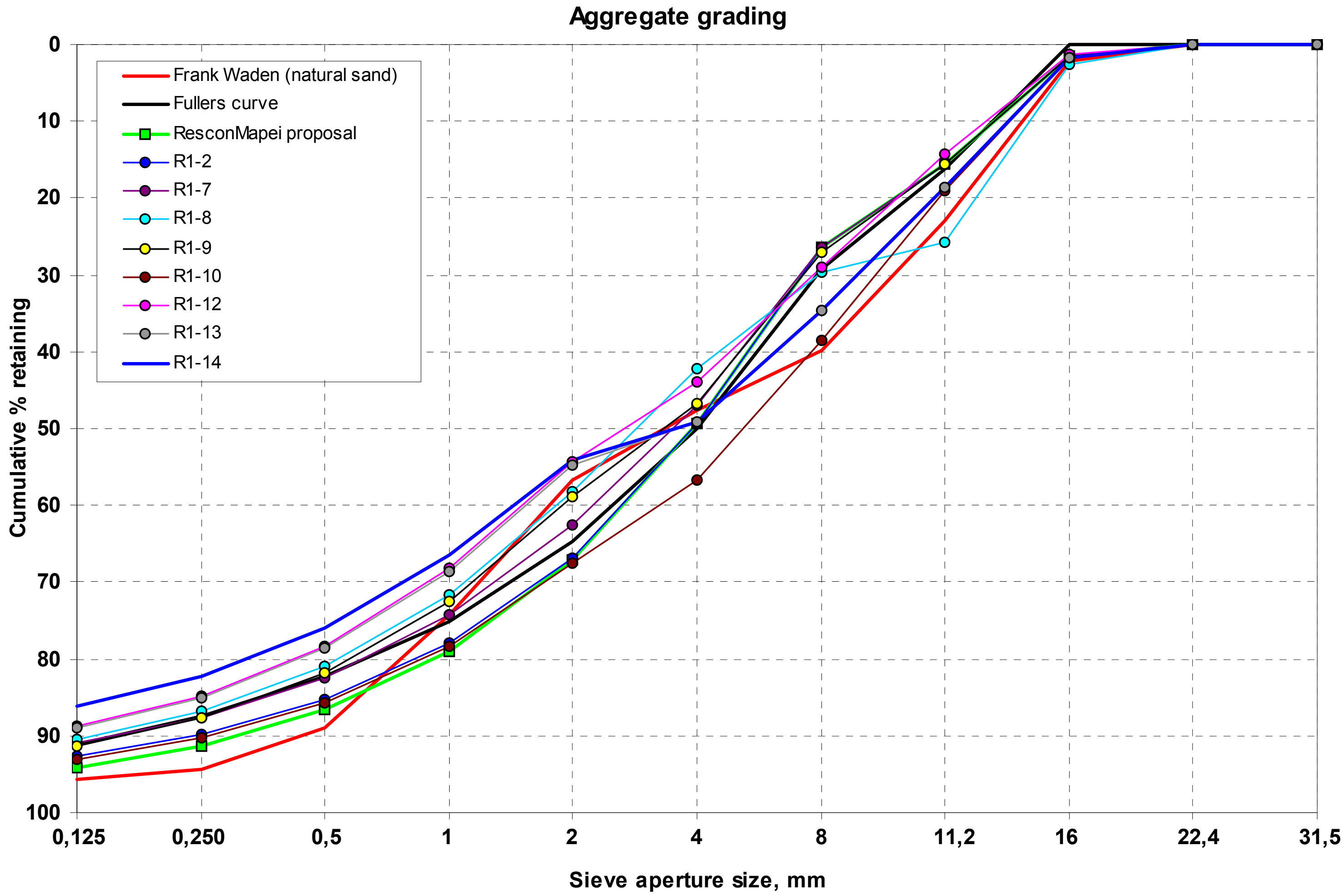


Figure 3-4 Grading curves of the concrete mixes tested to find the "starting point" for further research of the possibilities to use manufactured sand from Jelsa in plastic concrete mixes

Figure 3-5 Grading R1-2 at a matrix volume of 350 l/m^3 (w/c=0.57)

Figure 3-6 Grading R1-11 at a matrix volume of 410 l/m^3 (w/c=0.57)

Figure 3-6 Grading R1-14 at a matrix volume of 442 l/m^3 (w/c=0.57)

3.4.2 Comparison to Tau (NorStone) material

Before this study a successful preliminary testing in concrete had been carried out for crushed material from Tau. In order to compare crushed materials from different quarries two aggregate gradings (Tau 4 and Tau 8; see figure 3-7) with a D_{max} of 22.4 mm that worked fine with Tau material were adapted to D_{max} of 16 mm what was the maximum grains size according to the demand from the construction project in Jelsa.

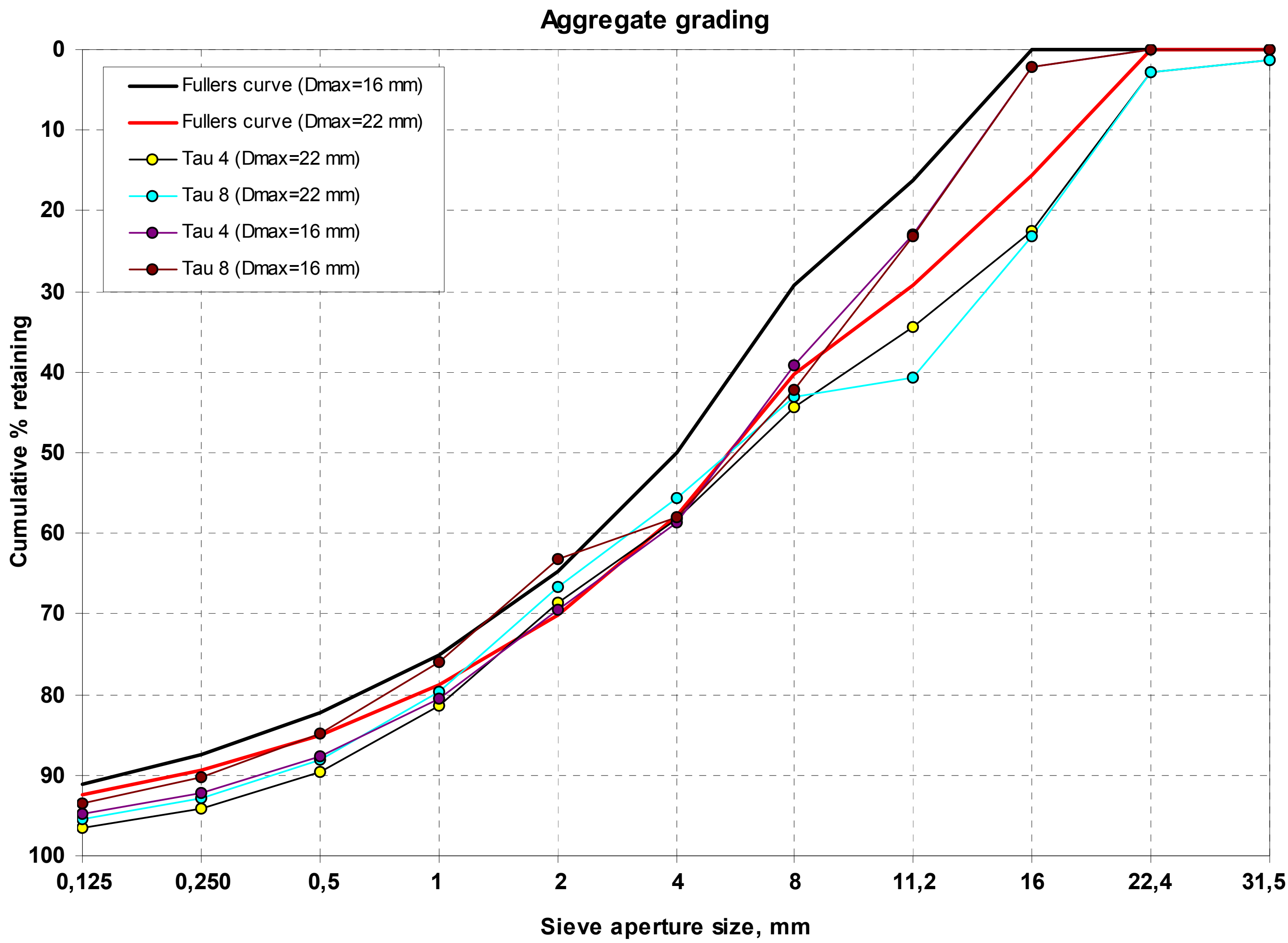


Figure 3-7 Tau 4 and Tau 8 grading curves with initial D_{max} of 22.4 mm and adapted curves with the D_{max} of 16 mm

The testing results (mix R1-15=Tau 4 and mix R1-16=Tau 8; both D_{max} of 16 mm) showed that even at a much higher matrix content 390 l/m^3 vs. 330 l/m^3 mixes with the Jelsa material did not form a homogenous plastic concrete (figures 3-8 and 3-9).

Figure 3-8 Grading R1-15 (Tau 4) at a matrix volume of 388 l/m^3 (w/c=0.57)

Figure 3-9 Grading R1-16 (Tau 6) at a matrix volume of 396 l/m^3 (w/c=0.57)

The tests with Tau material had been mixed using STD FA cement instead of STD at the D_{max} of 22.4 mm, so later on two more laboratory mixes (R1-39 and R1-40) were prepared to see if this has any positive effect on the concrete behavior. The results when Tau 4 mix design with STD FA cement and D_{max} of 22.4 mm was used showed a somewhat better result for tests R1-39 and R1-40 than for R1-15 and R1-16 but still it was not a completely usable and plastic concrete mix.

3.4.3 Washed/Unwashed 0/2 mm Material Ratio (Lowest Possible Matrix Volume)

As the R1-14 mix was somewhat an extreme that is too rich in fines (matrix volume of 442 l/m^3) the next step was to find the "lowest possible" matrix amount by changing the 0/2 mm washed/ unwashed material ratio and also to observe how this affects water demand of the concrete. Eight more concrete mixes were prepared for the case (figure 3-10; table 3-4).

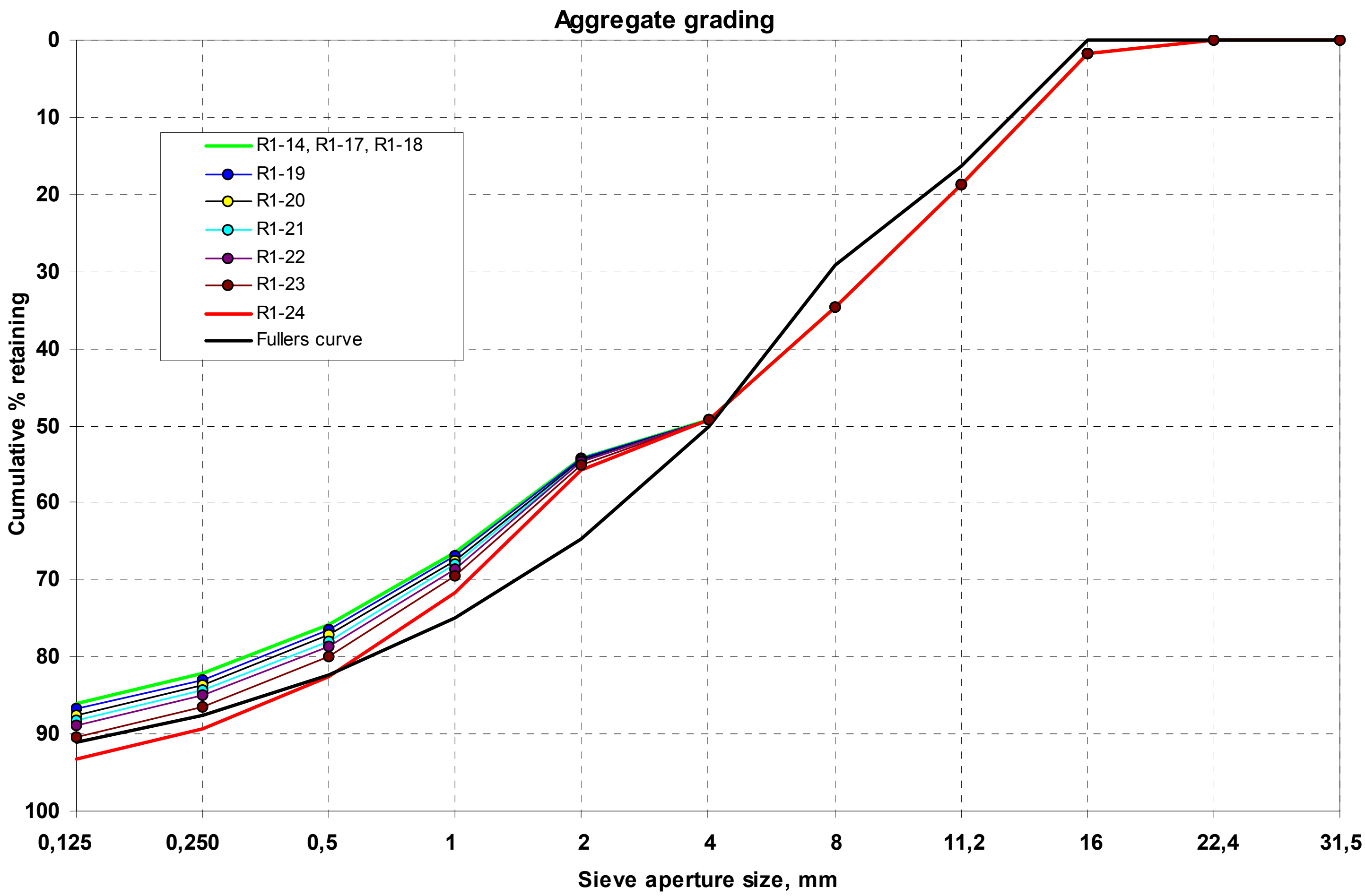


Figure 3-10 Grading curves of the concrete mixes tested to find the lowest possible matrix volume by changing the washed/unwashed 0/2 mm material ratio

First of all R1-17 and R1-18 (table 3-4) mixes were tested to go down with the cement content but still have a concrete that is by far on the safe side from the point of pumpability and stability of the mix. Mix R1-18 with a cement content 380 kg/m^3 and matrix volume of 427 l/m^3 was chosen as the reference for further testing in this step.

Next the test mixes from R1-19 to R1-24 (table 3-4) with different washed/unwashed 0/2 mm material ratios were prepared to observe mix stability for several lower matrix volumes and to see the water demand decrease with the lower dosage of the finer material.

It can be seen from table 3-4 how the ratio of unwashed/ washed 0/2 mm material was changed and what happened to the mix. It was not possible to look at the water demand from the point of an increase in slump/ slump-flow because the reference mix R1-18 (with the predictable highest water demand) was already with a slump of 240 mm, so the idea here was to go down with 0.1% of Dynamon SX-N dosage for each +5% of washed 0/2 mm material. It worked fine for the first three steps until the ratio of unwashed/ washed 0/2 mm was 35/15. Then down to 20/30 (figure 3-11) it was not possible to see a big decrease in the water demand probably because of a bigger friction between the particles due to the decreased matrix volume. The last extreme tried was a mix (R1-24) with only washed 0/2 mm material and as it can be seen from the figure 3-12 it was a failure – separation and excessive bleeding (figure 3-13), probably something like this was seen when the first testing of 100% crushed mix design had been carried out in the production in the mobile plant before (October 2009), because it was done using only unwashed 0/2 mm material.

Figure 3-11 Grading R1-23 at a matrix volume of 394 l/m^3 (w/c=0.57)

Figure 3-12 Grading R1-24 at a matrix volume of 380 l/m^3 (w/c=0.57)

Figure 3-13 Bleeding test for mix R1-24; height of the concrete layer was 15 cm, picture taken about 2 hours after putting the concrete in the bucket

Table 3-4

Mix Design and Flowability Testing Results for the Tests of Variable Unwashed/Washed 0/2 mm Material Ratios

ID	R1-14		R1-17		R1-18 (REFERENCE)		R1-19		R1-20		R1-21		R1-22		R1-23		R1-24	
Jelsa 0/2 (unwashed), kg/m^3 (%)	858.8	50	871.1	50	883.2	50	795.0	45	706.6	40	618.4	35	530.0	30	353.3	20		
Jelsa 0/2 (normal w.), kg/m^3 (%)							88.3	5	176.7	10	265.0	15	353.4	20	530.0	30	883.4	50
Jelsa 5/8, kg/m^3 (%)	257.7	15	261.3	15	265.0	15	265.0	15	265.0	15	265.0	15	265.0	15	265.0	15	265.0	15
Jelsa 8/11, kg/m^3 (%)	257.7	15	261.3	15	265.0	15	265.0	15	265.0	15	265.0	15	265.0	15	265.0	15	265.0	15
Jelsa 11/16, kg/m^3 (%)	343.5	20	348.4	20	353.3	20	353.3	20	353.3	20	353.3	20	353.3	20	353.3	20	353.3	20
Water, kg/m^3	228		222.3		216.6		216.6		216.6		216.6		216.6		216.6		216.6	
CEM I 42.5R (STD), kg/m^3	400		390		380		380		380		380		380		380		380	
w/c	0.570		0.57		0.57		0.57		0.57		0.57		0.57		0.57		0.57	
Matrix volume, l/m^3	**442**		**435**		**427**		**422**		**418**		**413**		**408**		**394**		**380**	
ResonMapei Dynamon SX-N, kg/m^3 (%)	3.2	0.8	3.12	0.8	3.42	0.8	3.04	0.8	2.66	0.7	2.28	0.6	2.28	0.6	2.28	0.6	2.28	0.6
Slump, mm	230		220		240		230		230		215		215		215		220	
Slump-flow, mm	410		350		470		430		365		340		350		430		505	
Slump (after 5 dumps), mm	250		240		250		250		250		250		235		230		245	
Slump-flow (after 5 dumps), mm	480		420		550		510		450		430		405		495		565	

The main conclusions from this step are:

- starting from a certain level the increase in unwashed 0/2 mm material content for 5% would lead to a need of increasing the Dynamon SX-N dosage for a +0.1% or approximately adding extra +4-7 l/m^3 of water;
- for the cement content of 380 kg/m^3 the "safety-level" (so we would still get a stable and workable concrete) of unwashed/ washed material (if 50% is the total of 0/2 mm aggregates) is 15/35 or about 9% of aggregates passing the 0.125 mm sieve;
- for the given w/c ratio of 0.57 and used gap-grading from 2 to 5 mm the necessary "lowest-possible" matrix volume is around 395 l/m^3.

3.4.4 Grading With the Lowest Water Demand

Another step completed within the laboratory trial program was the investigation on the flowability and water demand of different grading compositions for a given cement and 0/2 mm unwashed material content (reference mix R1-18; see table 3-4). The following options were compared:

- **full-graded mix-design** (R1-26);
- **gap-grading from 2-5 mm** (R1-27);
- **gap-grading from 2-8 mm** (R1-28);
- **gap-grading from 5-11 mm** (R1-29);
- **gap-grading from 2-11 mm** (R1-41).

The mix compositions and results from the tests are presented in table 3-5 and figures 3-14 and 3-15.

As it can be seen from the results the best aggregate composition for Jelsa material from the point of water demand and flow properties of the mix is the gap-grading from 2-8 mm.

Table 3-5

Mix Design and Flowability Testing Results for the Water Demand Tests

ID	**R1-26**		**R1-27**		**R1-28**		**R1-29**		**R1-41**	
Jelsa 0/2 (unwashed), kg/m³ **(%)**	883.2	**50**	883.2	**50**	883.3	**50**	883.3	**50**	883.3	**50**
Jelsa 2/5, kg/m³ **(%)**	194.3	**11**					265.0	**15**		
Jelsa 5/8, kg/m³ **(%)**	106.0	**6**	265.0	**15**						
Jelsa 8/11, kg/m³ **(%)**	229.6	**13**	265.0	**15**	441.6	**25**				
Jelsa 11/16, kg/m³ **(%)**	353.3	**20**	353.3	**20**	441.6	**25**	618.3	**35**	883.3	**50**
Water, kg/m³	216.6		216.6		216.6		216.6		216.6	
CEM I 42.5R (STD), kg/m³	380		380		380		380		380	
w/c	0.57		0.57		0.57		0.57		0.57	
Matrix volume, l/m³	**429**		**427**		**427**		**429**		**427**	
ResonMapei Dynamon SX-N, kg/m³ **(%)**	3.04	**0.8**	3.04	**0.8**	3.04	**0.8**	3.04	**0.8**	3.04	**0.8**
Slump, mm	230		220		240		230		230	
Slump-flow, mm	410		350		470		430		365	
Slump (after 5 dumps), mm	250		240		250		250		250	
Slump-flow (after 5 dumps), mm	480		420		550		510		450	

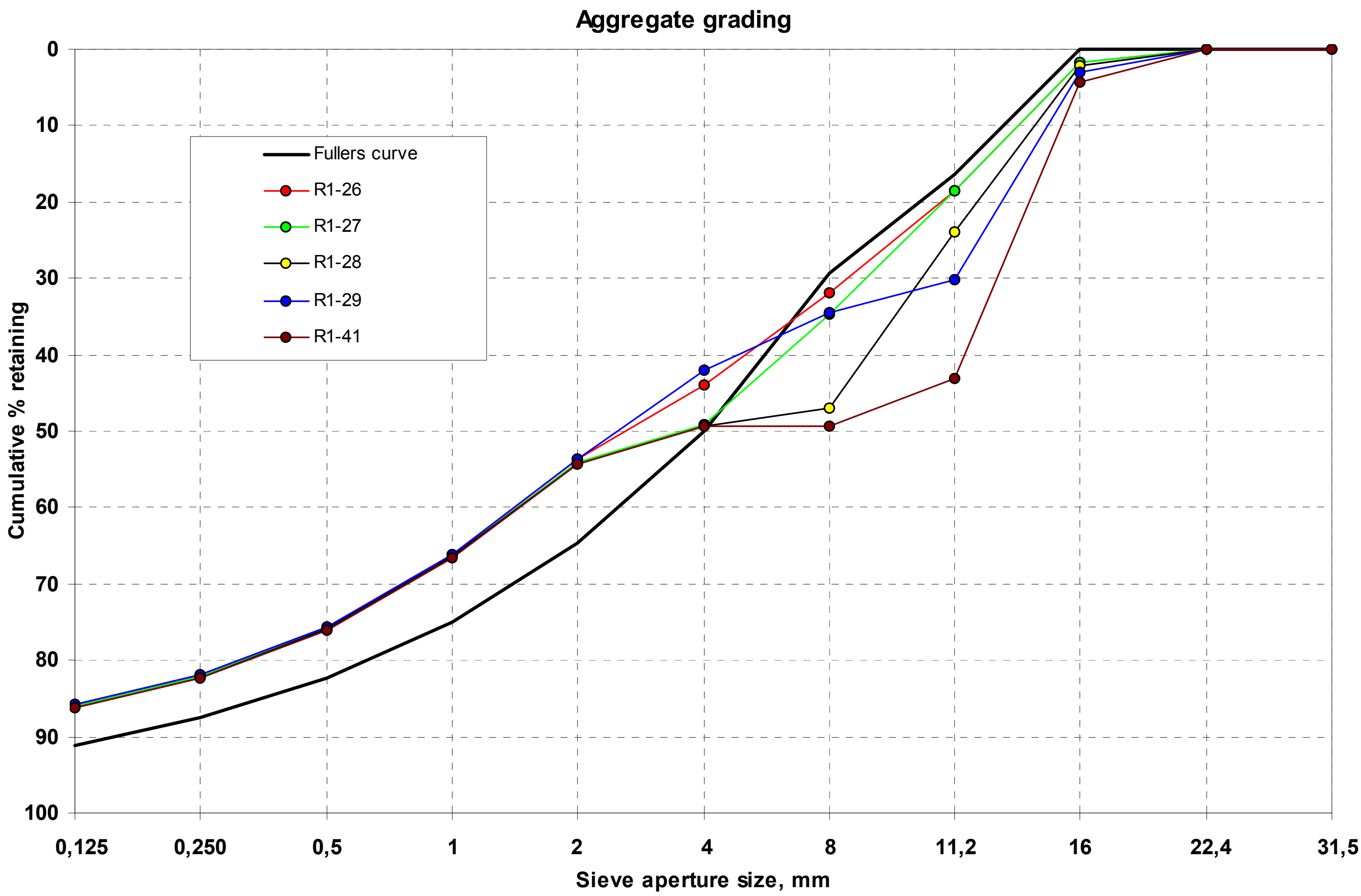


Figure 3-14 Grading curves of the concrete mixes tested to find the mix compositions with the lowest water demand

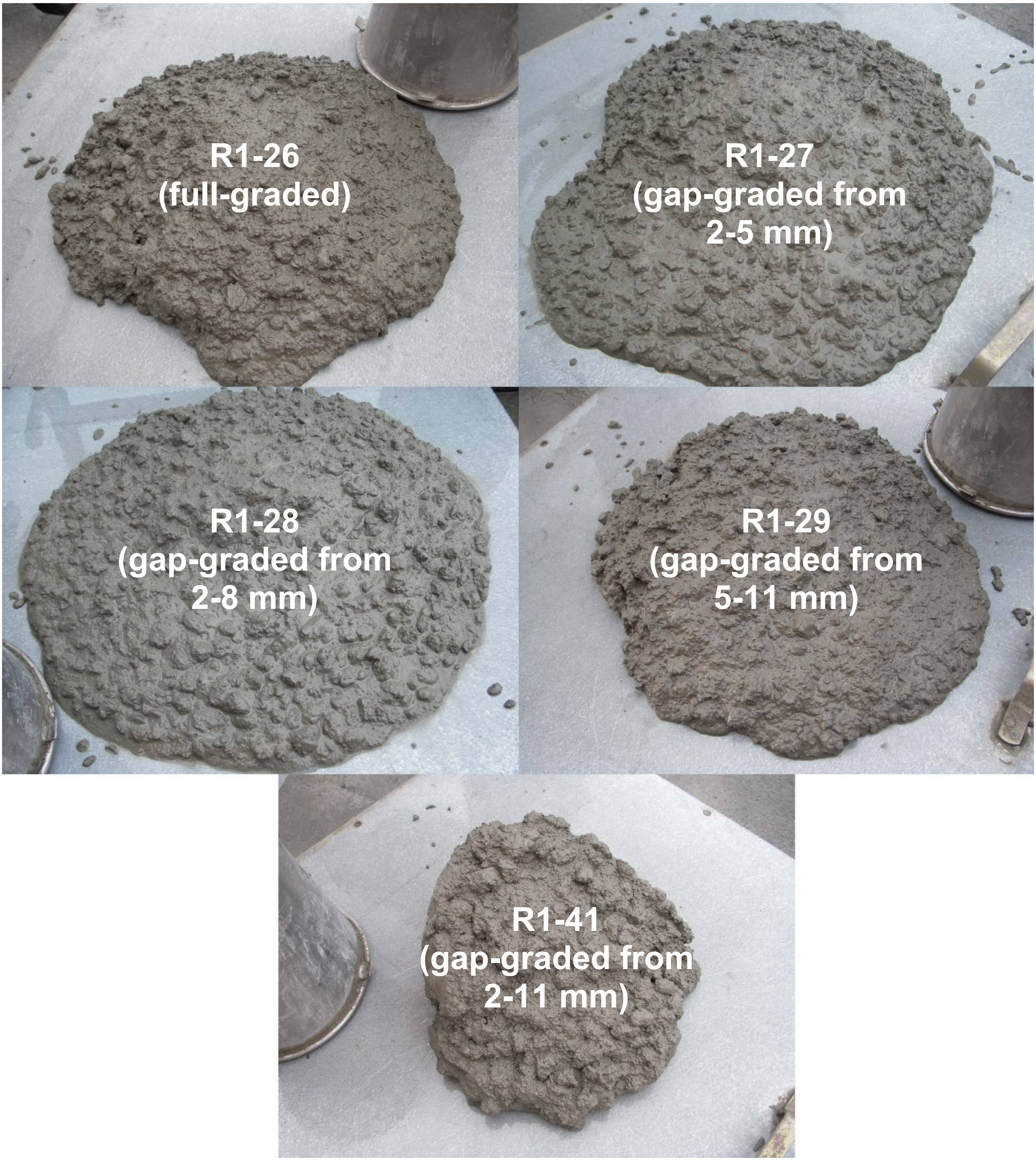


Figure 3-15 Slump-flow for different gradings (matrix volume and composition left invariable)

3.4.5 Cement Content Optimization

To see if there is any difference in the behaviour of concrete when the matrix consists more of crushed particle fines (≤0,125 mm) instead of cement grains and also to achieve an economical benefit (compared to natural sand concrete used before) test mixes R1-28; R1-30; R1-31; R1-32; R1-34 were completed (see table 3-6). The main goal was to go down with the matrix volume to the extreme value (395 l/m^3) that was determined by changing the washed/ unwashed 0/2 mm ratio and to see if it's possible to do the same by reducing the cement content (w/c left invariable).

Table 3-6

Mix Design and Flowability Testing Results for the Cement Content Optimization Tests

ID	R1-30		R1-31		R1-32		R1-35	
Jelsa 0/2 (unwashed), kg/m^3 **(%)**	902.0	**50**	918.0	**50**	883.3	**50**	926.0	**50**
Jelsa 8/11, kg/m^3 **(%)**	451.0	**25**	459.0	**25**	441.6	**25**	463.0	**25**
Jelsa 11/16, kg/m^3 **(%)**	451.0	**25**	459.0	**25**	441.6	**25**	463.0	**25**
Water, kg/m^3	207.8		200.4		192.9		196.7	
CEM I 42.5R (STD), kg/m^3	364.6		351.6		338.5		345	
w/c	0.57		0.57		0.57		0.57	
Matrix volume, l/m^3	**415**		**405**		**395**		**400**	
ResonMapei Dynamon SX-N, kg/m^3 **(%)**	2.92	**0.8**	2.81	**0.8**	2.71	**0,8**	2.76	**0.8**
Slump, mm	235		235		170		225	
Slump-flow, mm	400		385		330		340	
Slump (after 5 dumps), mm	250		250		200		250	
Slump-flow (after 5 dumps), mm	475		470		400		410	

Mix composition R1-32 with the matrix volume that had been taken as the extreme from the previous tests was no a 100% "safe-result" (figure 3-16). Although the concrete was plastic and flowable, there were some blockages in the slump flow shape. Only full-scale test could approve the pumpability of this mix.

As the safe border (when reducing the cement content) the matrix volume of 400 l/m^3 or cement dosage of 345 kg/m^3 at w/c=0.57 (mix R1-35; figure 3-17) were taken.

Figure 3-16 Grading R1-32 at a matrix volume of 395 l/m^3 (w/c=0.57)

Figure 3-17 Grading R1-35 at a matrix volume of 400 l/m^3 (w/c=0.57)

3.4.6 Superplasticiser Dosage for the Production

Before the start of the study, in the production with natural sand if there was a need to change the consistency of the concrete it was achieved by adjusting the water content of the mix to the necessary level (leaving everything else invariable). This approach however is not beneficial from the economical point of view as well as it could not be used when working close to the extreme value of the “minimal-possible” matrix volume.

To solve the problem three laboratory tests were prepared to find out how the dosage of Dynamon SX-N affected the workability of concrete so it would be possible to achieve the desired flowability only by changing the superplasticiser content.

The results of the tests are presented in table 3-7 and figure 3-18.

Table 3-7

Mix Design and Flowability Testing Results for the Dynamon SX-N Dosage Tests

ID	**R1-35**		**R1-38**		**R1-39**	
Jelsa 0/2 (unwashed), kg/m^3 **(%)**	926	**50**	926	**50**	926	**50**
Jelsa 8/11, kg/m^3 **(%)**	63	**25**	63	**25**	63	**25**
Jelsa 11/16, kg/m^3 **(%)**	463	**25**	463	**25**	463	**25**
Water, kg/m^3	196.7		196.7		196.7	
CEM I 42.5R (STD), kg/m^3	345		345		345	
w/c	0.570		0.570		0.570	
Matrix volume, l/m^3	**400**		**400**		**400**	
ResonMapei Dynamon SX-N, kg/m^3 **(%)**	2.76	**0.8**	2.07	**0.6**	2.42	**0.7**
Slump, mm	225		130		190	
Slump-flow, mm	340		210		365	
Slump (after 5 dumps), mm	250		160		230	
Slump-flow (after 5 dumps), mm	410		265		430	

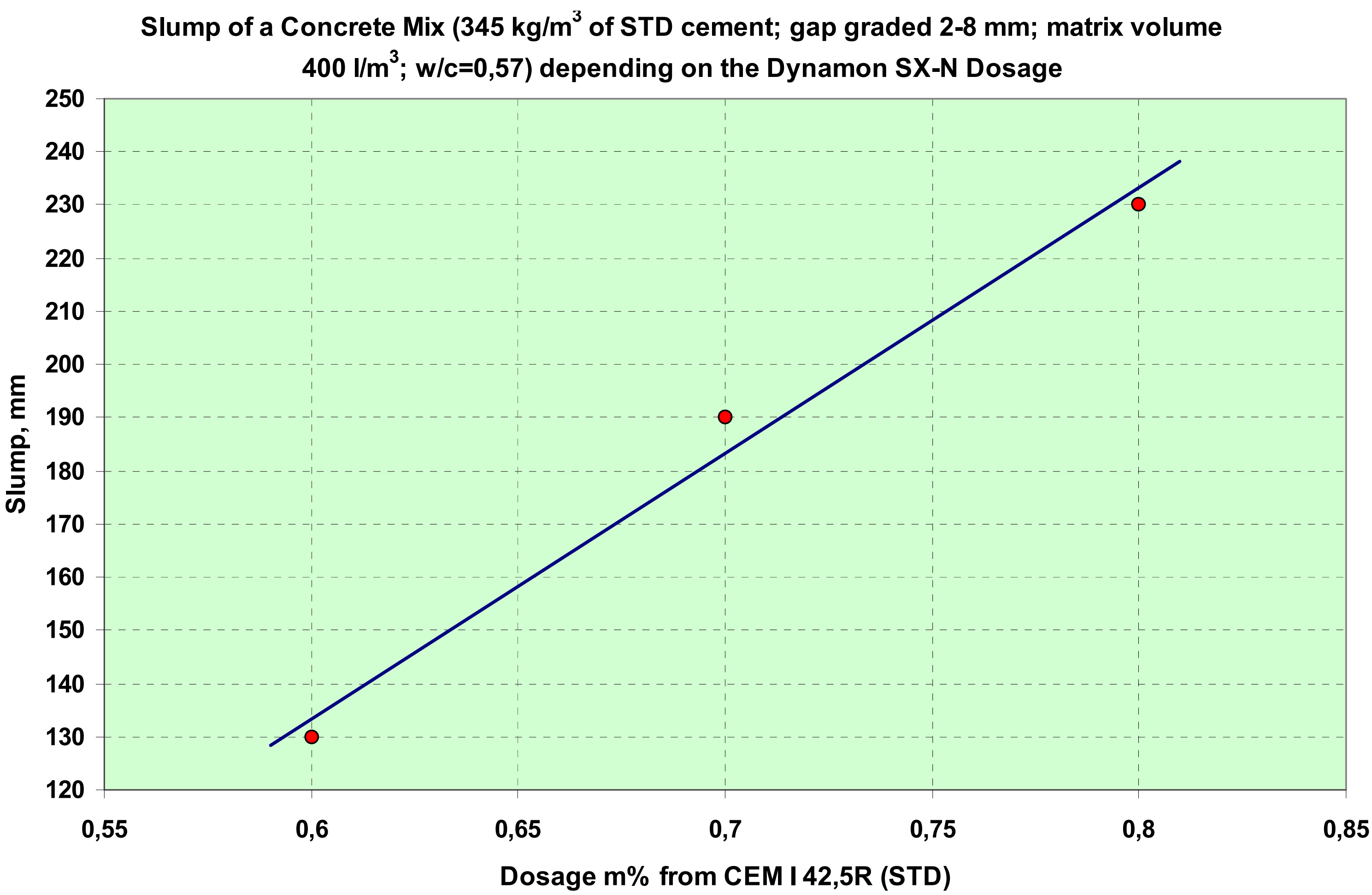


Figure 3-18 Slump of a concrete mix depending on the Dynamon SX-N dosage (everything else left invariable)

3.4.7 Lean Concrete

An additional demand for this type of concrete (C10/12) was that if the lean concrete layer had been casted in the evening it should already be “hard enough” until the morning of the next day. Because of this it was not possible to design a mix that actually corresponds to the C10/12 strength class.

A w/c ratio of 0.75 was chosen to achieve a compressive strength of approximately 3 MPa after one day of hardening at the temperature +5 ^{o}C or about 35 MPa if cured for 28 days in normal laboratory conditions (±20 ^{o}C). The matrix volume was chosen to be at the level of 394 l/m^3 what is a little lower than the extreme found for w/c of 0.57 (400 l/m^3).

A successful tests mix (R1-36) was prepared using the same gap-grading from 2-8 mm that gave the most desirable fresh concrete properties for the C30/37 mixes. The mix design and flowability testing results for tests R1-36 are presented in table 3-8 and figure 3-19.

Table 3-8

Mix Design and Flowability Testing Results for Test R1-36

ID	**R1-36**	
Jelsa 0/2 (unwashed), kg/m^3 **(%)**	926	**50**
Jelsa 8/11, kg/m^3 **(%)**	463	**25**
Jelsa 11/16, kg/m^3 **(%)**	463	**25**
Water, kg/m^3	210.2	
CEM I 42.5R (STD), kg/m^3	280.2	
w/c	0.750	
Matrix volume, l/m^3	**394**	
ResonMapei Dynamon SX-N, kg/m^3 **(%)**	1.68	**0.6**
Slump, mm	215	
Slump-flow, mm	390	
Slump (after 5 dumps), mm	240	
Slump-flow (after 5 dumps), mm	485	

Figure 3-19 Grading R1-36 at a matrix volume of 394 l/m^3 (w/c=0.75)

3.4.8 Self-Compacting Concrete (SCC)

As the matrix volumes tested for C30/37 concrete were rather high (up to 442 l/m^3 for mix R1-14) it was decided to try if this is enough to make a stable self-compacting concrete with Jelsa crushed material. Initially some extra of Dynamon SX-N was added to a couple of completed gap-graded mixes to see their potential of being used as a mix design for SCC. It was discovered (mix R1-41; see figure 3-19) that at the matrix volumes up to 427 l/m^3 it was not possible to get a completely satisfying result from gap-graded mixes. The result was not a complete failure but the large particles were not always carried to the peripheral area when the slump-flow was measured. It was also possible to notice an uneven distribution of the large particles in the mix as well as slight separation in the peripheral area (figure 3-20).

Figure 3-20 Grading R1-41 at a matrix volume of 427 l/m^3 (w/c=0.57) and slump-flow of 580 mm

To solve the problems observed a full-graded mix-design (R1-42) at a matrix volume of 444 l/m^3 was tested (table 3-9; figures 3-21 and 3-22). The result was completely satisfying – a stable self compacting concrete mixture.

Table 3-9

Mix Design and Flowability Testing Results for Test R1-42

ID	**R1-42**	
Jelsa 0/2 (unwashed), kg/m^3 **(%)**	859	**50**
Jelsa 2/5, kg/m^3 **(%)**	189	**11**
Jelsa 5/8, kg/m^3 **(%)**	103	**6**
Jelsa 8/11, kg/m^3 **(%)**	223	**13**
Jelsa 11/16, kg/m^3 **(%)**	343	**20**
Water, kg/m^3	228	
CEM I 42.5R (STD), kg/m^3	400	
w/c	0.570	
Matrix volume, l/m^3	**444**	
ResonMapei Dynamon SX-N, kg/m^3 **(%)**	4.8	**1.2**
Slump-flow, mm	650	

Figure 3-21 Grading R1-42 at a matrix volume of 444 l/m^3 (w/c=0.57) and slump-flow of 650 mm

Figure 3-22 Grading R1-42 at a matrix volume of 444 l/m^3 (w/c=0.57) and slump-flow of 650 mm

3.4.9 Compressive Strength Testing

For some of the laboratory mixes 100x100x100 mm concrete test cubes were made. The results available indicate an average 28-day compressive strength of 48.8 MPa for the w/c of 0.57 and 33.4 MPa for w/c of 0.75. The values could be slightly higher than for similar concrete with natural sand but the results should be analyzed before the final conclusions are made.

Table 3-10 contains all essential data available from compressive strength testing.

Table 3-10

Compressive Strength Testing Results

Sample ID	Sampling date	Testing date	Age, days	Density, kg/m^3	$f_{c,cube}$, MPa	Slump, mm	Slump-flow, mm	w/c	Notes
#12; R1-14	18/03/2010	25/03/2010	7	2502	**40.3**	230	410	0.570	**400 kg/m^3** of STD cement; **cured in water in laboratory conditions (+/- 20°C)**
#12; R1-14	18/03/2010	25/03/2010	7	2454	**35.7**			0.570	**400 kg/m^3** of STD cement; **cured in outside weather conditions (0 to +8°C)**
#12; R1-14	18/03/2010	15/04/2010	28	2480	**50.7**			0.570	**400 kg/m^3** of STD cement; **cured in water in laboratory conditions (+/- 20°C)**
#12; R1-14	18/03/2010	15/04/2010	28	2490	**50.7**			0.570	
#17; R1-14	18/03/2010	15/04/2010	7	2475	**41.5**	230	430	0.570	**390 kg/m^3** of STD cement; **cured in water in laboratory conditions (+/- 20°C)**
#17; R1-14	18/03/2010	15/04/2010	7	2435	**35.7**			0.570	**390 kg/m^3** of STD cement; **cured in outside weather conditions (0 to +8°C)**
#17; R1-14	18/03/2010	15/04/2010	28	2500	**49.5**			0.570	**390 kg/m^3** of STD cement; **cured in water in laboratory conditions (+/- 20°C)**
#17; R1-14	18/03/2010	15/04/2010	28	2500	**51.8**			0.570	
#28; R1-30	22/03/2010	31/03/2010	9	2461	**43.8**	235	400	0.570	**365 kg/m^3** of STD cement; **cured in water in laboratory conditions (+/- 20°C)**
#28; R1-30	22/03/2010	19/04/2010	28	2490	**50.7**			0.570	
#28; R1-30	22/03/2010	19/04/2010	28	2480	**49.5**			0.570	
#29; R1-31	22/03/2010	31/03/2010	9	2456	**40.3**	235	385	0.570	**352 kg/m^3** of STD cement; **cured in water in laboratory conditions (+/- 20°C)**
#29; R1-32	22/03/2011	19/04/2010	28	2470	**47.2**			0.570	
#29; R1-33	22/03/2012	19/04/2010	28	2490	**47.2**			0.570	
#32; R1-34	24/03/2010	31/03/2010	7	2471	**41.5**	225	330	0.570	**345 kg/m^3** of STD cement; batch size 20 litres; **cured in water in laboratory conditions (+/- 20°C)**
#32; R1-34	24/03/2010	31/03/2010	7	2452	**34.6**			0.570	**345 kg/m^3** of STD cement; batch size 20 litres **cured in outside weather conditions (0 to +8°C)**
#32; R1-34	24/03/2010	21/04/2010	28	2440	**49.5**			0.570	**345 kg/m^3** of STD cement; batch size 20 litres; **cured in water in laboratory conditions (+/- 20°C)**
#32; R1-34	24/03/2010	21/04/2010	28	2500	**41.5**			0.570	
Average w/c=0.570 (28d)					**48.8**				
#36; R1-36	25/03/2010	31/03/2010	6	2460	**26.3**	215	390	0.750	**Lean concrete**; **cured in water in laboratory conditions (+/- 20°C)**
#36; R1-36	25/03/2010	31/03/2010	6	2453	**19.3**			0.750	**Lean concrete; cured in outside weather conditions (0 to +8°C)**
#36; R1-36	25/03/2010	22/04/2010	28	2450	**33.4**			0.750	**Lean concrete**; **cured in water in laboratory conditions (+/- 20°C)**
#36; R1-36	25/03/2010	22/04/2010	28	2490	**33.4**			0.750	

#42; R1-42	26/03/2010	23/04/2010	28	2450	**46.1**			0.570	
#42; R1-42	26/03/2010	23/04/2010	28	2410	**41.6**			0.570	
#42; R1-42	26/03/2010	23/04/2010	28	2450	**49.5**		650	0.570	**SCC**; **cured in water in laboratory conditions (+/- 20°C)**
#42; R1-42	26/03/2010	23/04/2011	28	2490	**49.5**			0.570	
#42; R1-42	26/03/2010	23/04/2012	28	2490	**43.8**			0.570	

4. RESULTS IN GENERAL

As the main result of this study a usable and economically beneficial mix design (on 100% crushed material from Jelsa quarry) of a pumpable C30/37 structural concrete was developed. Table 4-1 and figures 4-1 and 4-3 present a comparison of the natural sand mix used before and the mix that could be the best solution according to the laboratory trials. Though, a full-scale testing (including pumping experiments) is necessary for an approval of the new approach.

Table 4-1

Comparison of Concrete Mix Designs

ID	Natural sand C30/37 reference concrete		Manufactured sand C30/37 concrete	
Jelsa 0/2 (unwashed), kg/m³ (%)			926.0	50
Jelsa 0/2 (normal unwashed), kg/m³ (%)	89.9	5		
Natural sand 0/8, kg/m³ (%)	965.5	53.1		
Jelsa 8/11, kg/m³ (%)	305.2	16.8	463.0	25
Jelsa 11/16, kg/m³ (%)	457.6	25.2	463.0	25
CEM I 42.5R (STD), kg/m³	**380**		**345**	
Water, kg/m³	191.5		196.7	
ResonMapei Dynamon SX-N, kg/m³ (%)	1.80	**0.47**	2.92	**0.8**
w/c ratio	**0.504**		**0.570**	
Matrix volume, l/m³	**341**		**400**	
Slump, mm	**210**		**230**	
Compressive strength $f_{c,cube}$, MPa	**54**		**48.8**	

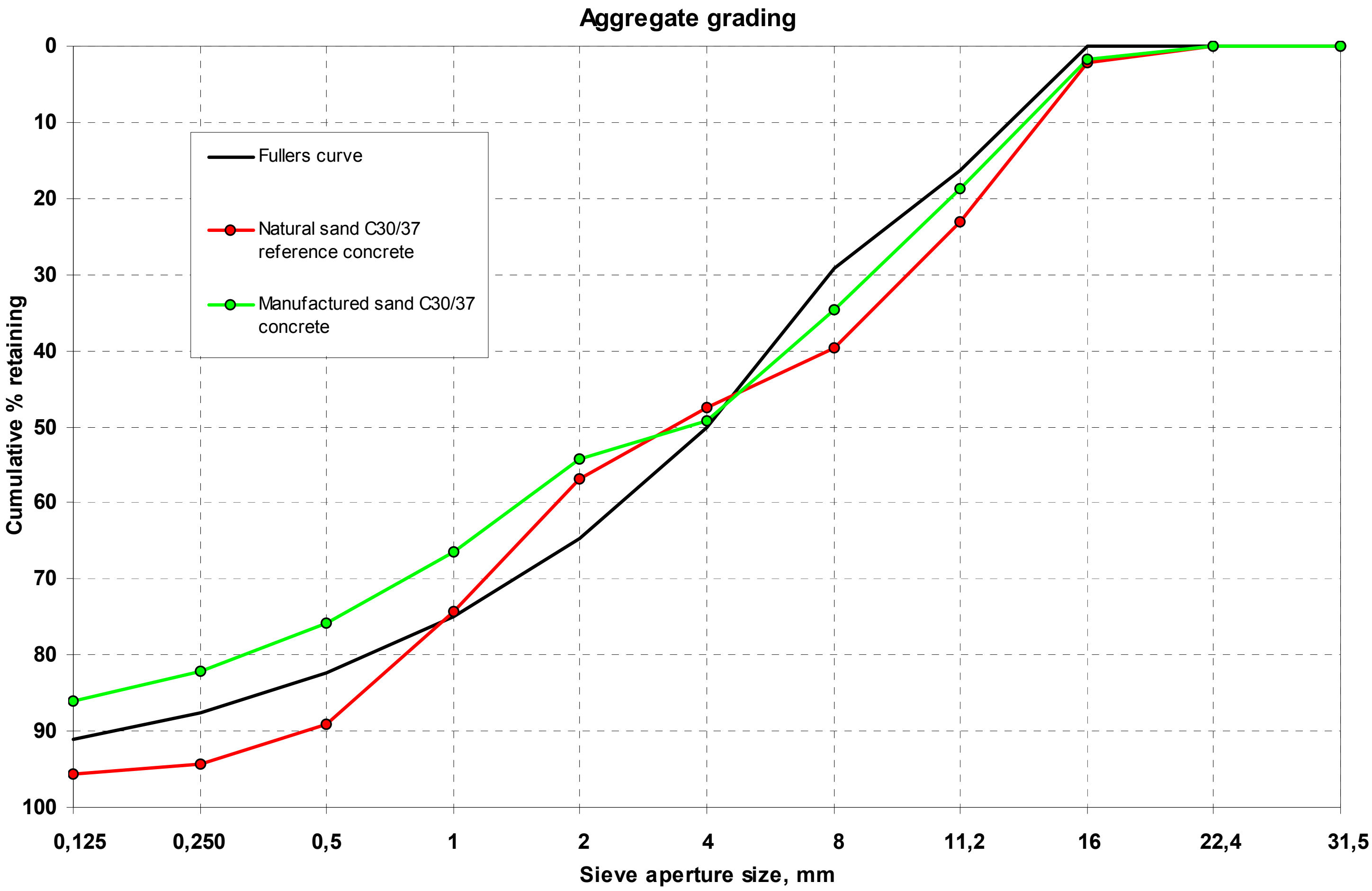


Figure 4-1 Grading curves of the natural sand and manufactured sand C30/37 concrete

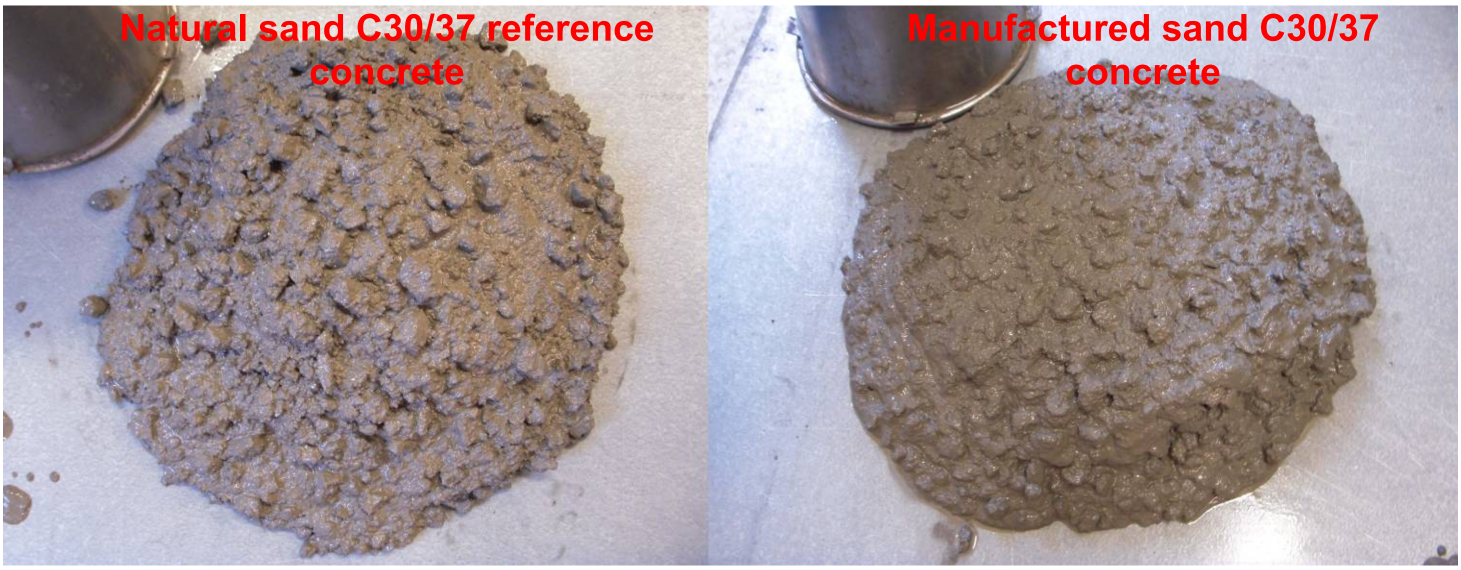


Figure 4-2 Slump-flow of the natural sand and manufactured sand C30/37 concrete

5. CONCLUSIONS

The preliminary tests performed show that if the manufactured sand from Jelsa quarry (with a sharp particle shape) is used for a dense grading, the result gives a harsh mix, requiring much of fines (matrix volume) to compensate the voids content - increasing the water demand.

Experience of traditional natural sand concrete mix design should not be automatically transferred for use with Jelsa material as the results most likely will show an undesirable result. A completely new approach should be developed.

The best aggregate composition for Jelsa crushed material from the point of water demand and flow properties of the mix is the **gap-grading from 2-8 mm**. Though, it should be also stated that gap-grading is not the key to obtain good results. For example, a straight-graded mix would give the same results but with an increased water demand (a need for higher matrix volume to achieve the same fresh concrete properties). The gap-grading is also less suitable for the production of self-compacting concrete (SCC).

Using **gap-grading from 2-8** mm could also be beneficial from the point of aggregate sales because 5/8 mm material has a good market for other products than concrete.

The gap-graded mix design includes a lot of 0/2 mm unwashed material that is very rich in fines (~26% passing the 0.125 mm sieve). When left outside in rain the material could acquire a moisture content of up to 13%. When the moisture was higher than 9% laboratory tests indicated repeatability problems. This could also be an issue in real concrete production as well as moist material blockage in the aggregate silos and dust problem in the storage if the 0/2 mm material is very dry in the summer time.

It was hard to compare fresh properties of natural and manufactured sand concrete using only simple tests methods available for this study. The "look" of manufactured sand concrete until a certain matrix volume is completely different and since there was no prior experience with this material it was hard to draw up a border at which matrix volumes the concrete is still pumpable. The results (minimal matrix volume of 395 l/m^3 for w/c=0.57, STD cement and gap-grading 2-8 mm) from the laboratory tests must be therefore verified by full-scale pumping experiments in the quarry building site.

Manufactured sand from different sources (Tau and Jelsa) can give different results in concrete (water demand) when the same grading is used. This means that the shape of the particles in some fractions is very important and crusher type, settings and the number of crushing steps will determine the suitability of manufactured sand for the concrete production. It is not totally clear which fractions are the most important.

The previous results from the manufactured sand tests in mortars (D_{max} of 8 mm) could not be applied straight-forward to concrete with a D_{max} of 16 mm.

SINTEF Building and Infrastructure is the third largest building research institute in Europe. Our objective is to promote environmentally friendly, cost-effective products and solutions within the built environment. SINTEF Building and Infrastructure is Norway's leading provider of research-based knowledge to the construction sector. Through our activity in research and development, we have established a unique platform for disseminating knowledge throughout a large part of the construction industry.

COIN – Concrete Innovation Center is a Center for Research based Innovation (CRI) initiated by the Research Council of Norway. The vision of COIN is creation of more attractive concrete buildings and constructions. The primary goal is to fulfill this vision by bringing the development a major leap forward by long-term research in close alliances with the industry regarding advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.