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Provoking and Foreseeing Sudden Changes in the Workability of Pumped Concrete

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ABSTRACT
It was attempted to provoke and foresee sudden loss of workability during concrete pumping through a series of full-scale tests. Batches of 2 m^3 concrete were produced at a ready-mix plant, transported by concrete trucks and pumped by industrial pumps, to reveal sudden loss of workability. Different mix designs, extension hoses and pump setups were utilised in a six series experiment. An experimental procedure for measuring loss of workability at a laboratory scale was developed due to the standardised procedures for slump measurements camouflaging loss of workability. The experiments revealed that pumping through a boom seems to have a positive effect by reducing probability of sudden loss of workability. Furthermore, the fine aggregate seems to have a strong influence on the phenomenon, especially in the range of 0.25 mm to 1 mm.

Key words: Sudden changes in workability, pumping, production, placement.

1. INTRODUCTION

It is estimated that around 70% of the concrete delivered in Norway is placed by pumping, and it is assumed that this share corresponds to the conditions in several other Scandinavian and European countries. Pumping allows for large volumes of concrete to be placed efficiently and flexibly, and with less risk of injuring staff, compared to manual placement.

It is well known that the pumping process influences the workability of concrete. This is found to be a result of both the high pressure, and the extra "mixing" that the concrete is exposed to during its way through the pump and the extension hose. Mostly, the concrete producer is able to foresee the result of these processes and compensate to ensure that the delivered concrete has properties as ordered.

However, sometimes sudden changes in workability appear during pumping, representing both an increase and a reduction in workability. This was the topic for the recent paper "Sudden Changes in Workability during Concrete Pumping – An Industrial Approach" [1]. Based on a document analysis of the QA system of a medium-sized Norwegian ready-mix concrete producer covering 1 500 000 m^3 of concrete produced over 10 years, and semi-structured interviews with a series of skilled operators, it was estimated that around 30% of Norwegian ready-mix concrete experiences sudden changes of workability during pumping. Often, skilled operators manage to manipulate the concrete, securing success during delivery. Still, there are costs related to delays caused by these incidents, and consumption of chemical additives, that are both costly and environmentally burdensome. The incidents that are not successfully handled during delivery, might require high-cost repairs or re-work.

Though sudden changes in concrete workability seem extensive and yield economic and environmental consequences, they seem to be only vaguely addressed in research. One explanation might be the fact that the problem appears only sporadically, and not until delivery on construction sites. The lack of research-based knowledge applied in industrial settings is visualised e.g. through the different approaches for measuring workability in laboratories vs. those applied at construction sites. An important tool for measuring flowability properties in laboratories is rheometers. These instruments are unknown in industrial applications, where slump or slump flow are the only available measurements for actual quantification. The most frequently used evaluation method for workability at construction sites is simply a visual evaluation performed by experienced staff. Visual evaluation is even described in EN 13670 (8.3) [2] as sufficient. This shortcoming of correspondence between research environments and industry application is acknowledged by Feys et al. [3], who describe a practical approach by using simple nomograms like the one in Figure 1, utilising pipe diameter, pipeline length, concrete workability as measured by slump flow, and the pressure delivered by the pump as the only variables. Of course, these constant variables are not suitable for addressing sudden changes in properties like workability.

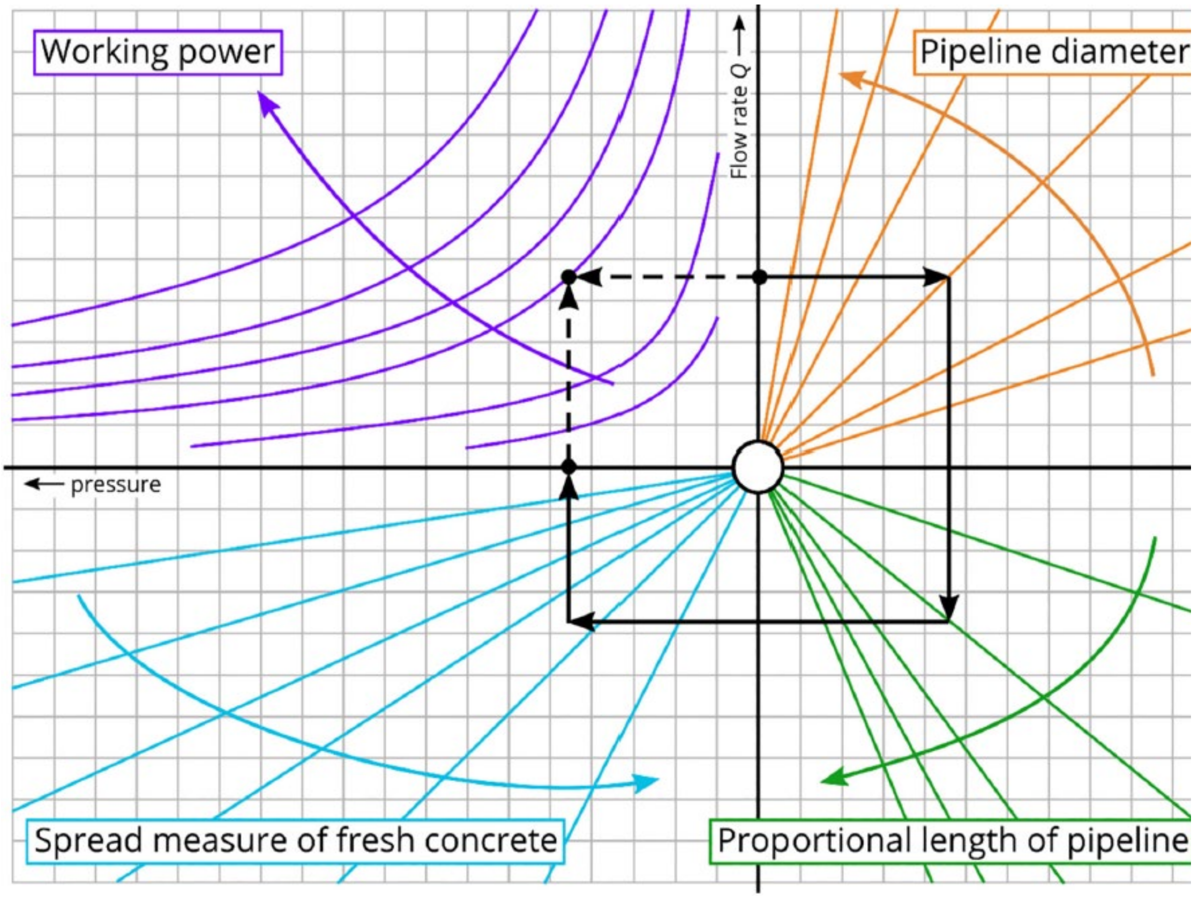

Figure 1 – Typical nomogram for practical planning of jobs where concrete is to be placed by pumping, according to [3].

The present paper is the second in a planned series of four papers that will constitute the basis for Mortensvik's PhD thesis, aiming to address and understand the problem with sudden changes in the workability of concrete during pumping – enabling industrial actors to foresee and establish procedures to omit these problems. This paper presents a series of full-scale experiments intended to provoke sudden changes in concrete workability during pumping and investigate methods for foreseeing them – suitable for industrial use.

From the investigations presented in the first paper [1], which was the precursor to the present, it was concluded that "Variations in the PSD of both fine and coarse aggregate occur. These appear to be the most relevant causes for sudden changes in workability". Thus, this will be the starting point when trying to provoke sudden changes in the series of full-scale experiments that establish the basis for the investigations presented in the present paper.

2. RESEARCH QUESTION

Which parameters trigger sudden loss of workability of concrete during pumping, and how can this potential be foreseen and omitted?

3. METHODS

To improve understanding of sudden changes in workability during concrete pumping, a series of full-scale experiments was performed. The first test was performed to establish a reference for further investigation of the concrete mix design. During this test with a mix design that is used for everyday production, fresh concrete properties were measured after the production of concrete and after pumping. The second test was conducted with minor changes to the mix design. Rather than just simulating transportation, the concrete was transported 15 km before testing of the fresh concrete properties before and after pumping. The pumped concrete was tested directly after the 28 meters boom, and finally after 10 meters of the extension hose.

Third and fourth tests were performed by using a different pump, without boom: just utilizing extension hoses onto the pipe bends which connect to the pump cylinders. The difference between the third and the fourth test was the mix design. Finally, the fifth and the sixth test were performed. The mix design was kept identical to the third and fourth tests, but this time a pump with a 43 metres boom was utilized. During the fifth and the sixth tests, the pressure that the fresh concrete was exposed to during pumping was documented. This was continuously measured and displayed on the operator's control unit, only on the pump used for tests five and six.

The fresh concrete properties measured were slump [4], slump flow [5], density [6], air content [7] and fresh concrete temperature. Compressive 28 days strength was measured for each mix on two cubes, as this is the industrial standard.

For ready-mix producers, slump is the traditional measurement for workability. On site, visual evaluation of workability is the most common practice, and slump measurement is performed occasionally. To gather as much information as possible, slump flow measurements were performed in addition to slump, even though the concrete was not necessarily self-compacting (SCC). Note that the slump cone was not filled again after the slump had been measured. The average diameter of the concrete after the slump test was performed was then measured as if a complete slump flow measurement was performed.

3.1 Literature review

A literature review focused on the industrial challenges of sudden changes in workability of concrete during pumping was executed as part of the paper [1] in 2023. It was found that despite reasonably high interest for challenges related to (constant) changes in workability of concrete during pumping, "the sudden changes in workability that sometimes appear, seems to be scarcely handled in the literature so far". Only one paper was identified where this challenge was recognised, yet still not discussed further.

In a well-designed laboratory experiment, Jacobsen et al. [8] investigated how different concrete mixes influenced the flow through pipes of three different materials. By flowing coloured concrete subsequently to normal (grey) concrete through the pipes, the flow distribution through the cross-section of each pipe was revealed by splitting the pipes in a longitudinal direction (after hardening). Despite the interesting insights given in this paper, it is worth mentioning that the impact of the pumping equipment and its set-up in a real-life situation is not considered. Also, much has happened to the constituents of concrete since this paper was written in 2009, e.g. concerning the chemical composition of additives and cement. Additionally, the properties of aggregate have been changed as machine crushing is becoming more and more the standard for both coarse and fine fractions.

In the paper by Jacobsen et al., the concrete was poured into a laboratory setup of pipes. In real-life situations, it might be anticipated that the pumping pressure and characteristics of the pumping equipment might influence the properties of the pumped concrete. Some of the papers identified in the literature search that was executed for our first paper [1], utilised experimental setups with industrial equipment. Shen et al. [9] described relations between flow velocity, hose length and workability of self-compacting concrete (SCC). The setup included pipeline lengths of 342, 545 and 1044 m. The diameter of the pipeline seems not to have been varied. The maximum pumping pressure was kept constant at 11 MPa. The pumping equipment was not specified, except that the stroke frequency was quantified – which leads to the assumption that it was a piston pump. The rheological properties were measured both by slump flow, V funnel and with an ICAR rheometer initially and after pumping. The ICAR measurement included a 30-second "pre-shearing period" at 0.5 revolutions/second, followed by a six-step decrease in revolution speed. Shen et al. [10] investigated how ten different mixes of high-strength concrete (HSC) were influenced by variations in pumping distances 348 m, 600 m and 924 m. Nothing is specified on the pumping equipment, and variations in the cross-section of the pipes are not described. The pressure varied up to 22.5 MPa. How the rheology was influenced by the pumping length was investigated in an ICAR rheometer, on a sample harvested from the concrete flowing out. Before measuring, the harvested samples were pre-processed in a stirring process. Choi et al. [11] investigated how the size of the coarse aggregate influenced the pipe flow of pumped concrete, utilising 170 m and 1000 m pipe lengths. The pipe diameter was kept constant at 125 mm, and a piston pump was used. Pump characteristics are stated. The pressure was varied up to 35 MPa. The rheological properties were measured initially at the freshly mixed material, for mortar (regarding the lubrication layer) and the complete concrete. Based on a literature reference, these initial values "were regarded as the rheological properties of the concrete in the pipe flow of the pumped concrete".

During the literature review update for this our second paper on the topic of properties of concrete during pumping, a few novel papers have been identified: [12] and [13]. However, these seem to be focused on analytical approaches to model real-life situations. Yet, despite high theoretical levels, neither appears to be calibrated towards industrial real-life set-ups. Liao et al. [13] certainly refer to an experimental study made by Ye (Ye H.: "Experimental and Numerical Simulation Study on Pressure Loss of Straight Pipe Pumped by Concrete", 2020) where the numerical modelling is claimed to be calibrated towards experiments made "under real pumping conditions". However, Ye's paper seems to only have been published internally at Huazhong University of Science and Technology. At least, we have not successfully identified it through any literature searches. Like lots of others, Liao et al. refer to the paper by Jacobsen et al. from 2009, indicating a scarcity of real-life experiments.

Conclusively, it seems that novel studies – theoretical or experimental - made on or calibrated towards real-life industrial settings with modern concrete materials are scarcely available. And though the existence of sudden changes in workability during real-life pumping situations has been recognised, this topic seems still not to be scientifically approached at all.

3.2 Experimental design: Manipulating mix design to provoke sudden changes in workability during concrete pumping

The mix design was based on the experience reported in the preceding paper [1]. Sudden loss of workability seems to be occurring more frequently when there is a reduction of coarse aggregate. The mix was consequently designed with 25% coarse aggregate reduction, strength C30/37 and exposure classes XF1, XC4.

Cement, water and the ratio between them were kept constant for all test mixes. Further, the aggregate fraction 8 mm / 16 mm was kept constant, but the three aggregate fractions smaller than 8 mm were adjusted to provoke sudden changes in workability during pumping. There was a permanent change at the mixing plant from fine aggregate 0/4 type 1 to fine aggregate 0/4 type 2 during the time period the full-scale tests were performed. This explains the minor differences in mix composition between Test 1, Test 3, and Test 5. These were intended to be identical, but variations occur in a real-world production situation.

Table 1 – Mix designs, all materials listed in kg/m^3.

Materials	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
CEM II/B-M(V-L)42.5 R	365	365	365	365	365	365
Water	188	188	188	188	188	188
Superplasticiser	2,19	2,19	2,19	2,19	2,19	2,19
Set retarding admixture	0,37	0,37	0,37	0,37	0,37	0,37
Coarse aggregate 8/16	606	606	606	606	606	606
Coarse aggregate 2/8	179	143	179	0	179	0
Fine aggregate 0/8	580	667	808	896	808	896
Fine aggregate 0/4 type 1	404	351	0	0	0	0
Fine aggregate 0/4 type 2	0	0	177	265	177	265

Aggregate, especially fine aggregate, does influence matrix volume. Furthermore, variations in the amount of each fraction influence the total particle size distribution. This will be further discussed in Section 4.4.

3.3 Experimental design: Equipment and setup for provoking sudden changes in workability

Three different pumps were used for testing: pump mixer, line pump and boom pump. A pump mixer (Figure 2, left) is agile and efficient, making it the backbone of the fleet. It has room for 5 m^3 of fresh concrete but can transport only 3 m^3 due to Norwegian weight restrictions for

roads. The boom is 28 metres, optionally followed by extension hoses. The stability of the vehicle during operation is secured by extending support legs requiring 1.4 m on each side.
The line pump (Figure 2, middle) is a specialized vehicle with low height and low gravitational centre. It is ideal for operating on barges, in narrow tunnels that only allow for low heights, and in similar locations. There is no boom on the line pump: the hose is mounted directly to the bends which connect to the concrete hopper outlet.
The 43 metres boom pump (Figure 2, right) is designed to deliver large amounts of fresh concrete. The support legs make a shape of an “X”, where the front spread is 9 m, and the rear is 9.5 m. Consequently, the placement of the pump must be carefully considered during the planning of the operation.

Figure 2 – Left: Pump mixer with 28 metres boom. Middle: line pump. Right: Boom pump with 43 metres boom.

A selection of 10 m extension hoses with diameters of 64 mm (2.5 inches) or 76 mm (3 inches) were used. Up to 60 m of extension hoses were used. The different pumps have different size cylinders, both diameter and length. The differences are listed in Table 2.

Table 2 – Specifications of different pump cylinders and hopper outlet

	Pump mixer	**Line pump**	**Boom pump**
Cylinder length	1600 mm (63 inches)	914 mm (36 inches)	2997 mm (118 inches)
Cylinder diameter	203 mm (8 inches)	178 mm (7 inches)	203 mm (8 inches)
Hopper outlet	178 mm (7 inches)	127 mm (5 inches)	178 mm (7 inches)

Figure 3 - Left: Setup of pumping with pump mixer and 10 m extension hose following the boom. Middle: Setup of line pump: concrete hopper, U-bend, reducer, and extension hose. Right: Setup of pumping with 43 m boom and up to 30 m extension hoses.

3.4 Experimental design: Reference mix design

The starting point was to establish a reference mix composition with a high potential for experiencing sudden changes in workability during pumping. In the preceding paper [1], based on a document search in the QA system with information on 1 500 000 m^3 of concrete produced during 10 years, it was indicated that one of the most produced mixes was relatively often exposed to these problems. This regards a C30/37, XF1, XC4, with a reduction of the coarse aggregate to improve pumping capability. Thus, this standard C30/37 pumping mix normally used for customers, was chosen for reference. The mix design is shown in Table 1, column "Test 1".

Further from [1], it was indicated that only small variations in the fine aggregate fractions might be the triggering cause for sudden changes in workability. Variations in the PSD of both natural and machined aggregates occur. The ready-mixed producer's tool for overcoming these variations is to combine several fractions with partly overlapping particle spans, and consequently being able to compensate for natural variations. A new mix design was developed as a slightly manipulated version of the standard C30/37 pumping mix. The three aggregate fractions smaller than 8 mm were adjusted to provoke sudden changes in workability during pumping, according to the indications found in [1]. The final mix design is shown in Table 1, column "Test 2".

3.5 Semi structured interviews

Subsequent to the experiments, some semi-structured interviews with pump operators experienced on operating all the 3 different pump types were conducted. This was to investigate whether the experimental results were in accordance with their everyday experiences.

4. RESULTS AND DISCUSSIONS

4.1 Establishing references with pump mixer

An intention with this series of experiments is to provoke sudden changes of consistency that might cause problems during pumping and establish a simple method for foreseeing these problems. This method should be suitable for execution both as production control at the mixing plant and quality control at the construction site, with equipment that is already available.

Measurements of the fresh concrete properties were performed two times: directly after production and loading onto a concrete truck, and after the concrete was transported 200 metres, then pumped through the 28 metres boom of the pump mixer and 10 m extension hose (total length of 38 m). Results from the property tests are shown in Table 3. There were no changes in concrete workability observable by visual evaluation when comparing the concrete properties directly after production with those after pumping. There are some minor variations between the measurement results. However, the test methods applied are rough, and minor variations in quantified results are considered equal. Control tests of both slump and slump flow were performed. Hence, there were no observable variations in workability before and after the pumping of the concrete in Test 1.

Table 3 -Test 1, fresh concrete properties

	Slump (mm)	**Slump flow (mm)**	**Fresh concrete temperature (°C)**	**Density (kg/m^3)**	**Air Content (%)**
5 minutes after production	210	370	22	2350	2.1
10 minutes after production	220	370			
5 minutes after pumping	220	380	17	2350	2.3
10 minutes after pumping	210	370			

The second pumping test was executed with the slightly adjusted mix design (Table 1, "Test 2"). A batch was mixed (2 m^3), transported 15 km, and pumped with a pump mixer (Figure 3, left). The results from the measurement of properties are shown in Table 4. There was a distinct drop in fresh concrete temperature after pumping. This was due to the steel hopper and steel pipes on the concrete pump having the same temperature as the ambient air. The full-scale test was performed on a typical November day in Norway, with overcast weather and a temperature of 2°C.

According to the measurements, there were only small changes in the workability. Again, there are some minor variations, but these might just as well be due to the inaccuracies of the measurement methods. This is demonstrated by the slump varying while the slump flow is constant between lines 1 and 2 in Table 3, versus the slump being constant and the slump flow varies when comparing lines 3 and 4. These small and contradictory variations seem to give little physical meaning and might be considered inaccuracies caused by limitations of the measuring method.

Table 4 – Test 2, fresh concrete properties

	Slump (mm)	**Slump flow (mm)**	**Fresh concrete temperature (° C)**	**Density (g/dm3)**	**Air Content (%)**
After production	220	370	23	2340	2.3
After transport	230	370	20	2340	2.2
After 28 metres boom	220	350	12	2340	2.1
After 10 metres extension hose	220	360	9	2350	2.8

If these measurements were from a real delivery setting, both the concrete producer and the contractor who tested the concrete at arrival would conclude that the concrete was delivered as specified. However, the visual evaluation reveals that something has happened to the workability. This is shown in Figure 4. The left picture shows the concrete received after pumping through the 28 m boom. The concrete is homogeneous and easily flowing. The right picture shows the same concrete, delivered only a few minutes later, pumped through the boom and an extra 10 m extension hose. The workability has changed. The concrete seems to have separated into lumps of harder material surrounded by small amounts of matrix, and the flow is heavily reduced. This concrete would be hard to process into e.g. an even slab with a smooth top finish. The contractor might successfully achieve this, but there is no doubt that this would require a lot of hard work.

Figure 4 - Left: Fresh concrete after 28-metre boom, homogeneous and no loss of workability. Right: Sudden loss of concrete workability has occurred during pumping.

Why didn’t the standard measuring methods reveal the changes in workability? One suspicion regards the processing of the concrete during measurement. According to the standard procedure, the slump cone is filled in three equal layers and each layer is compacted 25 times with a steel rod. This might result in the concrete being homogenised. This might be a reason why there is no loss of workability documented through the measurement. This processing during the measurement method might also simulate the work the contractor would have to do both manually and with a vibrator, to obtain the homogeneity necessary for achieving the smooth slab surface.

As a result of this suspicion, that homogenising the concrete through the test procedure of slump measurement might neutralise the changes in workability, a possible alternative test method for revealing potential sudden loss of workability during pumping was prototyped: Rather than using a slump cone, a standard bucket for measuring air content was filled with 8 litres of fresh concrete and then compacted. A plate was placed on top of the bucket before it was turned upside-down. The bucket was then lifted as a normal slump cone and the properties were measured. This was the first part of the measurement.

The second part was filling the bucket once again with fresh concrete and compacting. The top for measuring air was installed, and air was compressed in the bucket like a normal air content measurement. However, the water filling in the air space which is normally part of the measurement procedure, was not applied. Air was pumped and let into the concrete container according to standard procedure, however, repeated several times until the air pressure above the concrete reached the standardised 2 bar. Then, the top of the device was removed. No mixing or other form of homogenisation of the concrete was applied after exposing it to pressure. A thin plate was then placed on top of the bucket and the bucket turned upside-down. The bucket was then lifted as a normal slump cone and the fresh concrete properties was measured accordingly. This was the second and final measurement.

This method might fulfil the requirements for a simple test to foresee sudden loss of workability that might during pumping, before the actual pumping is executed.

Figure 5 – Left: Applying pressure to fresh concrete using standardised apparatus for air content measurement. Middle: The bucket has been turned upside down utilising a plate to keep the concrete in the container. Right: Concrete ready to be measured, after bucket has been lifted.

The results indicated that for concrete sensitive to sudden loss of workability during pumping, there was an observable difference between the first and second measurements. Concrete that was not sensitive to sudden loss of workability turned out to have close to identical measurement values.

The tests performed in these experiments indicate that directly after mixing, a potential for sudden loss of workability might be revealed. It is not necessary to expose it for actual pumping, or even transport it to the construction site. The test is executed with standard equipment already available at any ready-mix facility and at the construction site, available for the contractor's quality control.

4.2 Provoking sudden loss of workability with line pump

Utilizing the laboratory procedure for measuring concrete found to have potential for sudden changes in workability during pumping, another full-scale test was performed. As there were no visible changes to concrete properties by just pumping through the boom of the pump, a line pump was alternatively used as this allowed to just focus on the extension hoses.

Table 5 - Fresh concrete properties for Test 3 and Test 4

Measurements	Test 3	Test 4
Slump (mm)	250	240
Slump flow (mm)	530	520
Fresh concrete temperature (°C)	25	24
Slump «Bucket» before pressure (mm)	100	100
Slump «Bucket» after pressure (mm)	95	80
Slump flow «Bucket» before pressure (mm)	530	590
Slump flow «Bucket» after pressure (mm)	520	550

There were differences in workability for Test 4, according to measurements performed according to the new prototype test procedure. Although the numbers might be unfamiliar, compared to the standard test with a slump cone, the difference between measurements from the two steps in the new procedure showed a loss of workability for concrete exposed to laboratory scale pressure.

Table 6 – Results of pumping as a function of length and hose diameter

Total length	Hose diameter	Test 3	Test 4
10 metres	76 mm (3 inches)	No visible lumps. No loss of workability. Homogeneous concrete.	Visible lumps Loss of workability Inhomogeneous concrete
10 metres	64 mm (2.5 inches)	No visible lumps. No loss of workability. Homogeneous concrete.	Visible lumps Loss of workability Inhomogeneous concrete
20 metres	64 mm (2.5 inches)	No visible lumps No loss of workability Homogenous concrete	Visible lumps Loss of workability Inhomogeneous concrete
30 metres	64 mm (2.5 inches)	A few lumps No loss of workability	N/A
40 metres	64 mm (2.5 inches)	A few lumps No loss of workability	N/A
50 metres	64 mm (2.5 inches)	Visible lumps Loss of workability Inhomogeneous concrete	N/A
60 metres	64 mm (2.5 inches)	Visible lumps Loss of workability Inhomogeneous concrete	N/A

Figure 6 – Results from test 3. Left: 20 metres, 64 mm extension hoses, Middle: 40 metres, 64 mm extension hoses Right; 60 metres, 64 mm extension hoses.

As a first step, the concrete was pumped through a 10 m hose with diameter 76 mm (by operators daily referred to as 3 inches). Secondly, the 10 m hose was swapped to one with 64 mm (2.5 inches). Finally, extra 10 m 64 mm (2.5 inches) hoses were stepwise added up to a total of 60 m. The concrete workability was visually evaluated and documented by photographs for all steps of this experiment. The procedure was planned to be performed identically for both mixes Test 3 and Test 4.

At first step, no changes in workability were observed for mix Test 3. For mix Test 4, however, significant changes in workability were observed. Identical results were observed when the 10 m hose was swapped to the one with a smaller diameter, 64 mm (2.5 inches). When adding on an extra hose to a total of 20 m, the workability of Test 3 remained unaffected while Test 4 was not further influenced. At a total length of 30 m, Test 3 showed small signs of loss of workability. At total hose length 50 m, still 64 mm (2.5 inches), Test 3 reached significant signs of inhomogeneity and loss of workability. The changes are systematically described in Table 6 and documented with photos in Figure 6.

The change in concrete workability can easily be visually observed in Figure 6, both as the concrete is pumped out of the extension hose, and especially as it rests in the mould. During the day of testing, it had been raining, so there was some water in the moulds. This explains the free waters visible in the photos.

With the changing of the pump from a 28 m pump-mixer to a line pump, there emerged some interesting and unexpected results. The mix design used for Test 3 is currently the mix design used for everyday production. There have so far not been any reports or incidents of sudden loss of workability with this mix design, which is mainly pumped by 28 m pump mixers or boom pumps.

Through the semi-structured interviews, it was found that the results of Test 3 are in line with the current experiences with the pump operators, that a line pump is more prone to experiencing a sudden loss of workability compared to pump-mixers and boom pumps.

4.3 Provoking sudden loss of workability with boom pump

In an attempt to only focus on the mix design, Tests 3 and 4 were repeated with a boom pump. Tests 5 and 6 were performed with a boom pump that also measured the pressure yield on the concrete. The mixes used for Test 5 and Test 6 are identical to those used for Test 3 and Test 4, respectively.

Table 7 – Fresh concrete properties of Test 5 and Test 6.

Measurements	**Test 5**	**Test 6**
Slump (mm)	250	250
Slump flow (mm)	530	630
Fresh concrete temperature (°C)	14	14
Slump «Bucket» (mm)	110	100
Slump «Bucket» after pressure (mm)	110	80
Slump flow «Bucket» (mm)	640	590
Slump flow «Bucket» after pressure (mm)	630	550

The results from testing according to the suggested pilot method (air bucket) are shown in Table 7. The results are consistent with those of Test 3 and Test 4. The mixes used for Test 4 and Test 6 are identical and highly flowable. Still, the pilot test method indicates a potential for sudden changes in workability. When pumped, this was confirmed for all hose lengths, as described in Table 8.

Table 8 - *Results of pumping as a function of length and hose diameter, with 43 m boom*

Total length	**Hose diameter**	**Test 5**	**Test 6**
43 metres + 10 metres = 53 metres	76 mm (3 inches)	No visible lumps. No loss of workability. Homogeneous concrete.	Visible lumps Loss of workability Inhomogeneous concrete
43 metres + 10 metres = 53 metres	64 mm (2.5 inches)	No visible lumps. No loss of workability. Homogeneous concrete.	Visible lumps Loss of workability Inhomogeneous concrete
43 metres + 20 metres = 63 metres	64 mm (2.5 inches)	No visible lumps No loss of workability Homogenous concrete	Visible lumps Loss of workability Inhomogeneous concrete

Test 6 seemed to perform like Test 4, based on visual observations. There were no differences observed despite pumping with two different types of pumps. There was no loss of workability or inhomogeneous concrete observed with Test 5, at any hose length.

Table 9 – Highest and lowest pressure measured during pumping through 43 m boom and extension hoses.

Hose length	Hose diameter	Test 5 Lowest pressure	Test 6 Lowest pressure	Test 5 Highest pressure	Test 6 Highest pressure
10 metres	76 mm (3 inches)	6 bar	7 bar	14 bar	11 bar
10 metres	64 mm (2.5 inches)	6 bar	9 bar	14 bar	18 bar
20 metres	64 mm (2.5 inches)	13 bar	12 bar	20 bar	20 bar

Pressure increases with hose length, as shown in Table 9. All measured pressures seem to be in harmony with the experiences from other relevant research reports, like Shen et al. [5], Shen et al. [6] and Choi et al. [7]. There does not appear to be any major changes in pressure when comparing concrete experiencing sudden loss of workability with concrete that maintains workability. This probably contradict theories on correlating loss of workability with pressure to explain differences between the behaviour of the two mix designs.

Dimensions for the pump equipment used in these experiments are stated in Table 2 and partly illustrated in Figure 7. The line pump has no boom, where the cross section is successively reduced from pump cylinders to extension hoses over a distance of several metres. The line pump utilized in this research setup had a 178 mm (7 inch) diameter cylinder which was 914 mm long. The outlet of the concrete hopper was 127 mm (5 inches) in diameter, which means that the cross-section reduction through the S-tube was approximately 51 mm (2 inches), as illustrated in Figure 7 right part. A reducer is normally utilized for the line pumps to be able to attach extension hoses, bringing the cross section down to 76 mm (3 inches). Normally, extension hoses for concrete pumping in Norway are either 76 mm (3 inches), or 63 mm (2.5 inches).

For boom pumps, the cross-section of the cylinders is often 203 mm (8 inches). There is then a reduction through the S-tube and through the U-bend. The cross section is further reduced through a 1.5-metre reducer followed by the steel pipes (diameter 125 mm or 5 inches) that constitute the boom. At the end of the boom, where a flexible rubber hose is permanently attached, further reducers can be added, from 125 mm (5 inches) to 100 mm (4 inches) and then from 100 mm (4 inches) to 75 mm (3 inches). Here, either extension hoses are attached, or another reducer is used to bring the cross section down to 63 mm (2.5 inches).

Figure 7 – Left: Concrete hopper outlet with U-bend and ball stopper, reducer, and boom. Right: Line pump concrete hopper outlet with bend and reducer.

Pumping through a boom, which slowly reduces the cross section before the concrete is pumped through extension hoses, seems to reduce the potential for experiencing a sudden loss of workability. Explaining why, would probably require further research.

4.4 Foreseeing sudden loss of workability based on mix design

Concrete workability can be divided into mobility, compactability and stability. For concrete experiencing a sudden loss of workability, there seems to be a temporary separation of particles and matrix. By remixing the temporary separated concrete, it can restore its stability and thus mobility and compactability. Concrete in Test 2 was temporarily experiencing sudden loss of workability. However, after remixing as the procedure for testing slump, air content and compacting concrete for compressive strength was followed, there was no difference when compared to the other results for Test 2. For the concrete in Test 6, where it was pumped through 43 m boom and then 20 m extension hoses with diameter 63 mm (2.5 inches), temporary separation was visually observed. Concrete which experienced a loss of workability is documented in Figure 8. Both pictures were taken while the pumping proceeded. There seem to be a core of "dry" material, partly surrounded by matrix. This experience seems to contradict the anticipation made by Choi et al. [7], that the rheology of both the matrix part and the complete concrete "were regarded as the rheological properties of the concrete in the pipe flow of the pumped concrete". Corresponding pictures as those on in Figure 8 for concrete which did not experience loss of workability seemed homogenous throughout the cross-section of the hose and filled the circumference of the hose completely when pumped at the same flow.

Figure 8 – Left: Concrete experiencing sudden loss of workability with visible separation and inhomogeneous stability. Right: Concrete in the middle of the cross section seems particle dominated, whereas a large amount of matrix flows easily around the particle dominated part.

Focusing on the mix design, the main difference can be found in the particle size distribution for the aggregate. Traditionally producers focus on matrix and the fines in aggregate, and then, as this is a concrete mix design with coarse aggregate reduction, the amount of aggregates from 8 mm and coarser. When researchers search for explanations for all kinds of changes in workability in concrete during pumping, it seems they mostly focus on the coarse aggregate, like Choi et al. [11] who investigated how the size of the coarse aggregate influenced the pipe flow of pumped concrete. The sum PSD for all fractions, is stated in Table 10. The main difference between the two mix designs in Test 3 and Test 4, or Test 5 and Test 6 correspondingly, can be found in the amount of aggregate ranging from 0.25 mm to 1 mm. This is an indication that explanations for sudden loss of workability are to be found in this span of particle diameters. This was also one of the indications identified in the part of this research that led to paper 1 [1], which were used in the present work to design mixes with higher potential for experiencing sudden loss of workability. And it turned out to be confirmed.

Table 10 – Particle size distribution for mix designs, passing each sieve in percent (%).

Sieve (mm)	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
0	0	0	0	0	0	0
0.063	1	1	1	1	1	1
0.125	3	2	3	4	3	4
0.25	11	11	13	16	13	16
0.5	26	26	27	34	27	34
1	39	41	39	46	39	46
2	48	49	47	56	47	56
4	55	55	55	60	55	60
5.6	60	60	60	62	60	62
8	65	65	65	65	65	65
11.2	76	76	76	76	76	76
16	95	95	95	95	95	95
22.4	100	100	100	100	100	100

Even though there was a change of fine aggregate, from "Fine aggregate 0/4 type 1" to "Fine aggregate 0/4 type 2", ref Table 1, and further adjustments to the mix design in terms of the amount of each aggregate, the particle size distribution for the total amount of aggregate reveals only minor changes between Test 1, Test 3, and Test 5. As mentioned above, this is a result of the mixing operator combining different fractions with partly overlapping PSDs, to compensate for variations in each fraction. The particle size distribution from 8 mm and coarser is identical.

When focusing on fine particles that do not pass the 0.125 mm sieve, there is a difference between the mix designs that should be investigated further. This is demonstrated in Table 11.

Table 11 – Displaying sudden loss of workability and amounts of aggregate between 1 mm and 0.25 mm in %.

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Amount (%) of particles with diameter between 0.25 mm and 1 mm.	28	30	26	30	26	30
Experienced sudden loss of workability after 10 metres extension hose	No	Yes	No	Yes	No	Yes

The tolerance limit for deviation from a set amount of weighted aggregate according to [14] Table 27 is 3%. This could be part of an explanation of why sudden loss of workability can occur for some batches, but not necessarily for all batches throughout a normal day of production.

Taking further into account the tolerances for fine aggregate 0/4 according to [15] Table 4, where acceptable tolerances for both 0.25 mm and 1 mm is 20%. There is no tolerance limit set for 0.5 mm. For special purposes where the variation is to be reduced, the tolerance limits can be reduced according to[15] Table C.1. This reduces tolerances for 0.25 mm and 1 mm to 10% for 0/4. There is no tolerance limit set for 0.5 mm in [15] Table C.1.

For natural graded 0/8 the tolerance limit for 0.25 mm and 1 mm is 10% [15] Table 5. There is once again no tolerance limit set for 0.5 mm.

Due to the large tolerance limits for fine aggregate, there could be significant variations hidden within the production of fine aggregates. Transport method, by boat or truck, in combination with offloading to outdoor temporary storage at the ready-mix plant, could further hide the variations as aggregate of different batches are mixed. Aggregate silos are often filled using front loaders. Every time aggregate is handled, there is a possibility for changes in the particle size distribution.

According to the experiments reported in this paper, there seems to be an increased probability for sudden loss of workability when the amount of fine aggregate between 0.25 mm and 1 mm reaches 30%. Amounts passing 0.125 mm is considered to be part of the matrix phase of the concrete, when utilizing the particle/matrix model for mix design. Higher amounts of matrix at a set water/binder ratio will improve the stability of the mix design. [10] In a fresh state, constituents of concrete interact and are dependent on each other for stability, mobility and compactability. Although there might be ways to compose a mix design to the point where sudden loss of workability is triggered, aggregates are interacting with cement paste and superplasticiser. By changing either cement, water/binder-ratio or superplasticiser, this phenomenon of sudden change of workability during concrete pumping might be triggered at different particle size distributions. Acknowledging that fresh concrete is a highly complex matter to study, further research is needed to understand and mitigate the phenomenon. Pumping aids like silica fume and chemical admixtures to enhance pumping should be further investigated. Special focus should be directed towards the phenomenon that can be observed in figure 8, where there is a clear segregation of the concrete coming out of the extension hose and concrete placed in the formwork.

5. CONCLUSIONS

- A hypothesis developed from earlier research that a potential for experiencing sudden loss of workability lies in the composition of the fine fractions of aggregate was tested. A total of six full-scale experiments utilising industrial equipment were executed, and all supported the hypothesis. This conclusion is not considered exhaustive. Further potential might be found in other fractions of aggregate.
- Pumping through devices having a boom seems to have a positive effect on reducing sensitivity towards sudden loss of workability, compared to using line pump.
- Standard procedures to measure workability properties do not seem to reveal the potential of concrete mixes for experiencing sudden loss of workability during pumping. A simple method was developed and piloted through this research, which seems to reveal such potential. Both negative and positive potential was confirmed for all tests where this method was applied.
- Further research is needed to understand the phenomenon and how to mitigate the problem when it does occur.

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REFERENCES

1. Mortensvik, Ø. and Thorstensen, R. T., "Sudden Changes in Workability during Concrete Pumping–An Industrial Approach". *Nordic Concrete Research,* Vol. 69, No. 2, pp. 11-31.
2. NS-EN 13670:2009+NA:2010 Execution of concrete structures, Norway, C.-S., 2010.
3. Feys D, D. S. G., Fataei S, Martys NS, Mechtcherine V "Pumping of concrete: Understanding a common placement method with lots of challenges". *Cement and Concrete Research,* 2022.
4. NS-EN 12350-2:2019 Testing fresh concrete — Part 2: Slump test, Norway, C.-S., 2019.
5. NS-EN 12350-8: 2019 Testing fresh concrete — Part 8: Self-compacting concrete — Slump-flow test, CEN, 2019.
6. NS-EN 12350-6: 2019 Testing fresh concrete — Part 6: Density, CEN, Standard Norge, 2019.
7. CEN, "NS-EN 12350-7: 2019+AC:2022 Testing fresh concrete — Part 7: Air content — Pressure". ed. Standard Norge, 222019.
8. Jacobsen, S., Haugan, L., Hammer, T. A., and Kalogiannidis, E., "Flow conditions of fresh mortar and concrete in different pipes". *Cement and Concrete Research,* Vol. 39, No. 11, pp. 997-1006, 2009.
9. Shen, W. *et al.*, "How do discharge rate and pipeline length influence the rheological properties of self-consolidating concrete after pumping?". *Cement and Concrete Composites,* Vol. 124, p. 104231, 2021.
10. Shen, W. *et al.*, "Change in fresh properties of high-strength concrete due to pumping". *Construction and Building Materials,* Vol. 300, p. 124069, 2021.
11. Choi, M. S., Kim, Y. J., Jang, K. P., and Kwon, S. H., "Effect of the coarse aggregate size on pipe flow of pumped concrete". *Construction and Building Materials,* Vol. 66, pp. 723-730, 2014.
12. Zhaidarbek, B., Tleubek, A., Berdibek, G., and Wang, Y., "Analytical predictions of concrete pumping: Extending the Khatib–Khayat model to Herschel–Bulkley and modified Bingham fluids". *Cement and Concrete Research,* Vol. 163, p. 107035, 2023.
13. Liao, Y., Cheng, K., Sun, W., and Zhao, Y., "Study on pumping wear characteristics of concrete pipeline based on CFD-DEM coupling". *Scientific Reports,* Vol. 13, No. 1, p. 16119, 2023.
14. NS-EN 206:2013+A2:2021+NA:2022 Concrete - Specification, performance, production and conformity, Norway, C.-S., 2022.
15. NS-EN 12620:2002+A1:2008+NA2016 Aggregates for concrete, Norway, C.-S., 2016.