MASTER'S THESIS ACEX60

Experimental Study and Development of an Injection Grout Mix Proportioning Tool Based on Key Fresh-State Properties

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

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ABSTRACT

Injection grouting is widely used in underground construction to control groundwater inflow and improve rock mass stability. Despite its extensive practical application, grout mix design remains largely based on empirical experience rather than systematic, performance-based methodologies. This study investigated the relationships between grout composition and key fresh-state properties of cement-based injection grouts and developed a performance-based grout mix proportioning tool for practical applications. An extensive experimental program was conducted using two micro cement types combined with different water–cement ratios, accelerator systems, and superplasticizer systems. Rheological properties, including yield stress and plastic viscosity, were evaluated using the Bingham model at 5 and 20 minutes after mixing. Additional fresh-state properties such as water separation, filtration performance, density, air content, and setting behavior were also assessed. The results demonstrated that the water–cement ratio primarily governs the overall rheological level of the grout, while admixture type and dosage strongly influence early-age structuration, stability, and injectability. Certain grout combinations exhibited rapid stiffening and loss of pumpability, whereas others showed excessively low yield stress and increased segregation tendency. Filtration performance was also found to be closely linked to grout stability and particle interaction. Based on the experimental findings, a data-driven injection grout proportioning tool was developed to assist in the selection and optimization of injection grout mixtures according to target fresh-state performance criteria. The proposed approach contributes to a more systematic and practical methodology for injection grout design and has the potential to support improved efficiency, stability, and quality control in underground grouting operations.

Keywords: Injection grout, micro cement, rheology, yield stress, plastic viscosity, water–cement ratio, filtration, mix design, proportioning tool.

Contents

Preface

This master's thesis was carried out as part of the Master's Programme in Structural Engineering and Building Technology at Chalmers University of Technology. The work was conducted in collaboration with Heidelberg Materials Cement Sverige AB and focused on the experimental study and development of a performance-based mix proportioning tool for cement-based injection grouts.

The thesis work included laboratory testing, analysis of key fresh-state grout properties, and development of an Excel-based decision-support tool for grout mix selection. The experimental work was mainly performed using micro-cement systems with different water–cement ratios and admixture combinations. The project provided an opportunity to connect academic knowledge of cement-based materials, rheology, and grouting technology with practical industrial needs.

I would like to express my sincere gratitude to my academic supervisor, Arezou Baba Ahmadi, at Chalmers University of Technology, for her guidance, valuable feedback, and support throughout the thesis work. I would also like to thank my industrial supervisor, Jonny Nilimaa, at Heidelberg Materials Cement Sverige AB, for his technical guidance, practical support, and encouragement during the experimental work and tool development.

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I would also like to acknowledge the admixture suppliers Mapei, Sika, and Normet, who kindly provided admixture samples free of charge and contributed with technical support regarding product selection and dosage recommendations. Their input was valuable for designing an industrially relevant experimental matrix and for understanding the practical use of accelerator and superplasticizer systems in injection grout applications.

Finally, I would like to thank my loving family for their continuous support, patience, and encouragement throughout the thesis period.

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Notations

The following notations and abbreviations are used in this thesis report. Symbols are listed together with commonly used technical abbreviations related to the experimental program and injection grout mix proportioning tool.

w/c	Water–cement ratio by mass
τ_0	Yield stress
μ	Plastic viscosity
YS5	Yield stress measured 5 minutes after mixing
YS20	Yield stress measured 20 minutes after mixing
PV5	Plastic viscosity measured 5 minutes after mixing
PV20	Plastic viscosity measured 20 minutes after mixing
INJ30	Micro-cement type used in the experimental program
UF20	Ultra-fine micro-cement type used in the experimental program
UF12	Ultra-fine micro-cement type is considered for further testing
SP	Superplasticizer/ flow agent
SA	Set accelerator
RTGC	Real Time Grouting Control
RQ	Research question
d95	Particle size below which 95% of the particles pass
Pa	Pascal
Pa·s	Pascal second
mPa·s	Millipascal second
µm	Micrometer
ml	Milliliter
vol.%	Volume percentage

1 Background

Injection grouting is a critical technique in underground construction, particularly in tunneling, mining, dam engineering, and soil stabilization projects, see Figure 1.1. Micro cement-based injection grouts are fine-particle suspensions designed to penetrate fractures, joints, and voids under pressure, thereby reducing water inflow and enhancing ground stability. In hard rock tunneling, pre-injection grouting forms an essential component of the tunnel driving cycle, where boreholes are drilled ahead of the excavation front, and grout is injected prior to the next blasting to ensure hydraulic sealing and structural reinforcement.

Figure 1.1 Usage of injection grouts as construction material.

The functional performance of injection grout is governed primarily by its fresh-state behavior. Key properties include rheology, filtration stability, water separation resistance, density, air content, and setting time. These parameters directly influence pumpability, penetrability, resistance to segregation, and the ability to form an effective sealing structure in fine fractures. Failure to control these characteristics may result in operational delays, ineffective sealing, clogging, or excessive material consumption.

Despite the practical importance of injection grout performance, mix design procedures remain largely empirical and experience driven. There is currently no standardized predictive framework that systematically links mix composition variables such as cement type, water–cement ratio, and admixture system to measurable fresh state performance. This gap often leads to trial and error adjustments in the field and limited reproducibility between projects. As identified in the thesis planning phase, there is a clear need for a performance-based, data-driven approach that translates experimental findings into practical mix design guidance. The present study addresses this need by experimentally investigating a wide matrix of grout formulations and developing a prototype proportioning tool based on quantified fresh-state parameters.

1.1 Research Gap

Several strong conclusions can be drawn from the reviewed literature. First, fresh-state properties govern the practical performance of injection grout and must be treated as coupled rather than independent variables. Second, rheology is essential but insufficient on its own; filtration tendency and penetrability are at least as important for fracture sealing. Third, suspension stability cannot be judged only from conventional bleeding tests without considering geometry and field context. Fourth, cement fineness and admixture chemistry have non-linear effects, so intuitive assumptions such as "finer cement penetrates better" or "more fluid grout grouts better" are often unreliable. Fifth, time matters: hydration, flocculation, and structural build-up can change performance significantly within the first minutes after mixing.

Despite these advances, the literature also shows several unresolved issues that justify the current thesis. The first gap is methodological integration. Existing studies usually investigate one property, one mechanism, or one formulation family at a time. There is limited guidance on how to combine rheology, filtration, water separation, setting, and density-related variables into a unified selection system. The second gap is interpretive. Many studies report measured values but do not convert them into recommended operating windows for different grouting scenarios. The third gap is practical implementation. Although grouting theory has advanced substantially, there remains a shortage of user-friendly decision tools that can recommend candidate recipes from laboratory data.

A fourth gap concerns standardization. Some research papers show that rheological results depend on protocol and shear history, while others show that bleeding and penetrability depend strongly on measurement geometry. This means that a proportioning tool can only be as reliable as the internal consistency of the test methods used to build it. The present thesis is therefore not only a database exercise; it is also an exercise in defining a coherent testing framework.

Based on the literature, the research need can be stated clearly: there is a need for a property-based grout proportioning tool that uses systematically generated laboratory data to identify mixes most likely to satisfy target fresh-state requirements, while acknowledging trade-offs among injectability, stability, filtration resistance, and time-dependent behavior. The current thesis is well-positioned to address this gap because it combines micro-cements, multiple admixture systems, repeated fresh-state measurements, and the explicit ambition to turn experimental results into a practical recommendation tool. This gap limits reproducibility, increases the risk of performance variability, and reduces the efficiency of injection grout optimization for site-specific conditions.

1.2 Problem Statement

The absence of a predictive and performance-based framework linking injection grout composition to fresh-state behavior presents a practical challenge in underground construction projects. Designers and site engineers must select injection grout recipes without quantitative guidance regarding expected rheology, stability, filtration performance, and setting behavior. This may lead to suboptimal mix designs, operational delays, excessive material consumption, or inadequate sealing performance.

Therefore, there is a need to investigate the relationships between mix parameters and fresh-state properties systematically and to translate these relationships into a practical proportioning approach that supports data-driven decision-making in injection grouting applications.

1.3 Research Questions

The following four research questions guide the present study:

1. How do water-cement ratios and admixture dosages affect the yield stress and plastic viscosity of injection grout?
2. How do admixture combinations influence the setting time and water separation stability of injection grout?
3. How do micro cement type and grout composition influence filtration performance in the Filter Pump Test?
4. How can experimental findings be translated into design guidelines or a mix proportioning tool to predict fresh injection grout performance?

2 Literature Review

This chapter synthesizes the literature most relevant to the development of an injection grout mix proportioning tool. The review focuses on cement-based and micro-cement grouts for rock injection grouting and related injection applications, with particular attention to rheology, bleeding, filtration, penetrability, setting behavior, and the influence of the water/cement ratio and admixtures. The discussion is intentionally critical: rather than listing findings paper by paper, it identifies what is established, what remains uncertain, and where existing knowledge is insufficient to build a practical decision-support tool.

2.1 Grouting in rock engineering and property-based mix selection

Cement-based grouting is used in tunnelling and underground construction to reduce water ingress, limit permeability, and improve the stiffness or continuity of fractured rock. In Scandinavian and particularly Swedish and Norwegian practice, pre-excavation grouting is a central water-control measure, and grout performance is commonly judged by whether the required sealing effect is achieved in the field. However, field success depends strongly on fresh-state behavior before hardening, because the grout must first be pumped, remain sufficiently stable during handling, enter narrow fractures, resist excessive erosion or filtration, and develop adequate structure with time. This makes fresh-state characterization central to injection grout design rather than a secondary laboratory exercise.

Classical grouting theory links grout spread to the rheological parameters of a Bingham-type suspension, groundwater conditions, aperture geometry, and injection pressure. In the Real Time Grouting Control framework, yield stress, plastic viscosity, and penetrability are treated as key material inputs for estimating spread and defining stop criteria. This theoretical tradition is highly relevant for the present thesis because it establishes that mix design cannot be reduced to a single index, such as flow time or slump. An injection grout with low apparent viscosity may still perform poorly if it bleeds excessively, filters at constrictions, or experiences rapid structural build-up during pumping.

At the same time, a persistent gap exists between injection grouting theory and day-to-day material selection. In practice, contractors and laboratories often rely on a limited number of simple tests and accumulated experience, while research commonly examines one property at a time under controlled conditions. The development of a proportioning tool requires a broader synthesis: the tool must convert multiple measured fresh-state properties into practical recommendations, and the literature must be read with that application in mind.

Another important observation is that the literature spans different application domains. Some studies concern tunnel pre-grouting in rock, others crack injection or levee permeation grouting, and others still repair grouts designed for rapid setting or anti-dispersion under flowing water. These studies are valuable, but transferability cannot be assumed automatically. A formulation optimized for subway repair or cement–bentonite permeation may not be directly suitable for low-bleeding micro-cement rock grouting. Therefore, a critical review needs to distinguish between general mechanisms and context-specific design rules.

2.2 Cement-based injection grouts

Injection grout is fundamentally a concentrated suspension of cement particles in water, often modified by superplasticizers, accelerators, stabilizers, or other admixtures. In the rock grouting literature, the water/cement ratio is usually expressed by mass and is treated as a primary design variable because it affects both particle spacing and the balance between flowability and stability. Draganović, A. (2009) describes grout as a water–cement system in which the particles are partially hydrated and covered by reaction products from the moment of contact with water. This early-age evolution matters because the grout used in practice is never a perfectly inert suspension: hydration, flocculation, and particle interactions begin during mixing and continue during pumping and injection.

The role of cement fineness is more complex than it first appears. Very fine cements are often introduced to improve access to small fractures, and this logic is valid in a geometric sense because the particle size distribution defines the smallest constrictions that can potentially be passed. Yet finer cements also have much larger specific surface area and therefore stronger surface activity, faster early hydration, and greater tendency to flocculate. Draganović, A. and Stille, H. (2011) work is especially important here because it demonstrates that finer cement does not necessarily mean better penetrability.

This point is highly relevant for the present thesis, since the injection grout tool includes multiple micro-cement types. Literature based only on d95 or Blaine fineness would be insufficient for tool development. Instead, the proportioning logic must recognize that cement type is not merely a categorical input; it changes the interaction among rheology, filtration, time-dependence, and probably admixture efficiency as well.

Table 2.1 Fresh-state properties most relevant to injection grout selection and tool development.

Property	Primary physical meaning	Why it matters in practice	Limitation if used alone
Yield stress	Stress required to initiate flow or maintain plug movement	Controls injectability, pressure demand, and spread behavior	Strongly dependent on shear history; static and dynamic values can differ
Plastic viscosity	Resistance to flow once yielding has occurred	Affects pumping, fracture flow, and time to fill available volume	Low viscosity does not guarantee low filtration or low bleeding
Bleeding/water separation	Tendency for water to separate from the solid phase	Influences stability, void formation, and sealing quality	Bleeding tests with a cylinder may not represent thin fractures directly
Filtration / penetrability	Tendency to form plugs at constrictions and the ability to pass narrow apertures	Directly linked to the ability to grout fine fractures	Highly sensitive to aperture geometry, pressure, cement type, and testing time

Setting /structural build-up	Rate of stiffening with time	Determines the pumpability window and early stability after placement	Fast set may aid retention, but also increase blockage risk

2.3 Rheology of cement-based grouts

2.3.1 Yield stress, plastic viscosity, and Bingham behaviour

Many studies describe cement-based grout as a viscoplastic material that can be approximated by the Bingham model over a useful range of shear rates. Mohammed, M. (2014) reported Bingham-type behavior for the tested grouts, with plastic viscosities between 0.151 and 0.464 Pa·s and yield stresses between 5.2 and 36.7 Pa, while also demonstrating that composition strongly changes the balance between yield stress and viscosity. The practical value of the Bingham model lies in its compatibility with grouting design equations and with simplified field interpretation: yield stress governs the threshold for movement and plug formation, whereas plastic viscosity governs resistance during continued flow.

However, the literature also shows the limitations of treating Bingham parameters as fixed material constants. Rahman, M. (2015), Rahman's work is particularly important because it demonstrates that yield stress depends on shear history and that two ranges of yield stress may exist: a static value associated with a more structured state, and a dynamic value associated with a sheared state. This distinction is not a minor rheological nuance; it has direct design consequences. If laboratory measurements are taken after strong pre-shearing, the resulting yield stress may underestimate the resistance that develops in slowly moving grout at the fracture front. Conversely, if only static values are considered, pumpability may be underestimated. A proportioning tool based on rheological targets must therefore specify the measurement protocol and the intended interpretation of the result.

Rahman, M. (2015) also argued that a Bingham fit is meaningful only over an appropriate shear-rate interval and that the relevant design value depends on the prevailing shear rate at the grout front. This is a strong warning against overinterpreting a single flow curve. For the present thesis, it suggests that the 5 min and 20 min rheology measurements are not merely duplicate quality-control checks but important indicators of structural development over time. In other words, the tool should not recommend a mix solely because its initial rheology is attractive if its 20 min response moves too quickly into a high-yield regime.

2.3.2 Thixotropy, aging, and time-dependent rheology

The transient nature of grout rheology is a recurring theme across the literature. Cement grouts evolve due to reversible flocculation, irreversible hydration, and admixture-controlled dispersion or structuring. Mohammed, M. (2014) emphasized that the properties of grout are time-dependent from the moment of mixing because physical interactions and chemical reactions start immediately. Rahman, M. (2015) in-line UVP+PD work further shows that rheological properties can change measurably with water/cement ratio and hydration during flow, not only in a static beaker test.

This time dependence is one reason why direct transfer of rheological concepts from concrete or paste rheometry to rock grouting must be done cautiously. In grouting, the relevant question is not simply “what is the viscosity?” but “what is the viscosity at the time and shear state relevant to pumping and fracture penetration?” This is why the present thesis is correctly focused on early-age rheology at defined times. A practical tool should reflect this operational window rather than use a single equilibrium value. It may also be useful later to incorporate a ‘rheology drift’ indicator, for example, the relative increase in yield stress between 5 and 20 min, because this could help distinguish robust mixes from mixes that are only briefly workable.

2.3.3 Simple flow tests versus advanced rheometry

The literature generally supports a layered testing strategy. Simple methods such as the Marsh funnel, flow cone, capillary flow, and mini-slump are attractive because they are quick and feasible in laboratories or on-site. Mohammed, M. (2014) found that a large Marsh funnel provided viscosity-related values close to those obtained by viscometer testing for certain grout types, and they concluded that simple field methods can be useful when properly calibrated. The practical mix-design method proposed by Satyarno, I. (2014) also relies on ASTM C939 flow-cone measurements because they are straightforward for repeated mix proportioning work.

Nevertheless, these studies do not justify replacing rheometry with simple flow tests in all cases. Mohammed, M. (2014) explicitly notes that a Marsh funnel provides only a single data point and cannot, by itself, specify rheology. This is a critical limitation for injection grout design, where yield stress and plastic viscosity often need to be interpreted separately. Flow-cone-based approaches are therefore best viewed as screening or calibration tools rather than complete descriptors. For the present thesis, this suggests that rheometer-derived values should remain central in the database, while simpler indices can be treated as supporting or validation variables.

2.4 Stability of grout suspensions: bleeding

Bleeding and water separation are among the oldest and most widely discussed fresh-state phenomena in cementitious systems, yet the grouting literature shows that their interpretation is application-dependent. Classical works by Powers, T. (1939) and Steinour, H. (1945) linked bleeding to sedimentation, consolidation, capillary drainage and the amount of excess water in the suspension. Draganović’s synthesis is especially valuable because it revisits these foundational models from the perspective of rock grouting and asks whether standard cylinder measurements are actually relevant to thin rock fractures.

A key contribution from Draganović, A. (2009) is the argument that standard bleeding tests may not represent what happens in fractures. In a tall cylinder, gravity-driven settlement develops over a comparatively large sample height. In a thin fracture, however, the geometry is fundamentally different, and the grout may bleed, refill, or interact with continuing inflow during grouting in ways that are not captured by a standard column. He therefore concludes that results from conventional methods are not directly relevant to bleeding in rock joints and that interpretation must be fracture-specific. This is a major critical insight for the present thesis. It means that any tool using water-separation data should avoid treating such values as direct predictors of field void formation. Instead, they should be used comparatively, as indicators of relative suspension stability under the chosen laboratory protocol.

This criticism does not make bleeding tests useless. On the contrary, water separation remains a practical indicator of whether a grout is likely to be unstable, prone to settlement, or unsuitable for sustained pumping and sealing. The point is that the test must be interpreted at the correct level. For a proportioning tool, the safest approach is to use water-separation thresholds as screening limits or penalty factors rather than convert them into direct field performance predictions.

The ASTM procedures summarized in the uploaded material include water separation in a graduated cylinder and pressure-bleed testing. These procedures are helpful for organizing laboratory work, but it should be noted critically that the uploaded ASTM summary is not the normative standard text itself. For a formal thesis, the official standard documents should be cited where possible when the methods chapter is written. For literature-review purposes, however, the summary usefully highlights that different forms of 'bleeding' are measured under very different boundary conditions, and that the chosen test method shapes the meaning of the result.

2.5 Filtration tendency, penetrability, and fracture sealing ability

For rock grouting, filtration tendency and penetrability are arguably more decisive than general workability. A grout may appear fluid in a beaker yet still fail to enter or pass a constricted fracture because particle clusters bridge, plug, and progressively filter the suspension. Draganović, A. (2009) doctoral thesis and the related work by Draganović, A. and Stille, H. (2011) are among the most important sources on this topic because they move beyond generic flowability and examine grout movement through short- and long-slot devices intended to simulate constrictions in fractures.

The central lesson from this work is that penetrability is governed not only by particle size but by the interaction among aperture geometry, pressure, water/cement ratio, cement fineness, hydration and flocculation. Draganović, A. and Stille, H. (2011) report, for example, that INJ30 grout with w/c = 0.6 showed better penetrability than finer UF12 and UF16 systems under the same conditions. For UF12 with w/c = 1.2, the assumed critical aperture was around 250 µm, giving a ratio between critical aperture and d95 far higher than would be expected from particle size alone. The explanation offered is that hydration and flocculation can dominate, causing plug building even in very fine cements. This is a crucial finding for any mix recommendation system: 'finer' cannot be treated as inherently 'better for narrow fractures'.

The literature also suggests that penetrability has a stochastic component. Draganović, A. and Stille, H. (2011) observed cases where nominally similar tests gave somewhat different results, indicating that plug formation is at least partly random and that grout compatibility may vary even for the same cement type. This variability has methodological implications. It suggests that filtration tests should ideally be repeated and interpreted probabilistically, especially if they are to be used in a decision tool.

The relevance of pressure is likewise nuanced. Higher pressure can increase penetration rate and may erode partially formed plugs, but it does not eliminate the underlying material limitations. Recent modelling and experimental studies continue to support this view. A 2024 study on cement-based slurry penetration with time-dependent viscosity concluded that penetration radius increases only slowly once pressure exceeds a certain level, implying diminishing returns from simply increasing pressure. This aligns well with the older Scandinavian grouting literature, which emphasizes that grout properties and fracture geometry must be matched rather than compensated for by pressure alone.

Overall, the literature strongly supports including filtration-related outputs in the present thesis database. As the final tool is intended to recommend top candidate recipes, filtration and penetrability should receive greater weight than generic fluidity when the target application is permeation into fine rock fractures.

2.6 Setting behaviour, anti-dispersion and post-injection stability

Setting time occupies an intermediate position between fresh-state behavior and early hardened performance. For injection grout, the setting must be slow enough to avoid blockage during mixing and pumping, yet fast enough to stabilize the material after placement. The recent Buildings paper by Song, W. (2025) on subway repair grouts is useful here because it treats the design problem explicitly as a multi-objective optimization involving flowability, setting time, anti-dispersion, and early strength. Their analysis ranked water/cement ratio as the most influential factor, followed by HPMC dosage and then polycarboxylate superplasticizer dosage. Although the grout system differs from the micro-cement systems of the present thesis, the general lesson is highly transferable: mix design for grouting is a coupled problem with strong trade-offs rather than a sequence of independent optimizations.

That study is particularly valuable because it quantifies interactions among factors and highlights contradictions between desirable properties. For example, measures that increase anti-dispersion can simultaneously reduce flowability. This mirrors the broader grouting literature, where mixes that are highly stable or fast structuring can become less injectable. The practical implication for tool development is that the decision logic should not reward every improvement equally; it should instead apply property windows appropriate to the use case. A mix that is excellent in one application domain may be poor in another.

Recent work by Zhang, X. (2024) adds another dimension by showing that fresh cement-based grout in flowing-water conditions can experience significant erosion and viscous fingering after injection has stopped, even when existing criteria would predict acceptable performance. Reductions in grouted area of up to 50% after 10 minutes and 64% after 60 minutes were reported in their fracture-simulation tests. This finding is important because it challenges the common assumption that grout behavior after pumping stops is comparatively simple. For field grouting in water-bearing rock, post-injection resistance to erosion may deserve greater attention than it has received in conventional laboratory screening.

For the current thesis, these studies support the inclusion of setting-related variables and possibly a future refinement of the tool toward application classes. A tool intended for dry or low-flow conditions may prioritize penetrability and low bleeding, whereas a tool for water-bearing conditions may also need stronger weighting for anti-dispersion or erosion resistance.

2.7 Influence of mixture parameters

2.7.1 Water/cement ratio

Across nearly all sources, water/cement ratio emerges as the dominant first-order variable. It directly changes solids concentration, interparticle spacing, hydration environment, density, bleeding tendency, and both yield stress and plastic viscosity. Song, W. (2025) found the water/cement ratio to be the most sensitive factor for flowability, setting, anti-dispersion, and early strength. Similar emphasis appears in the Scandinavian grouting literature, where yield stress and penetrability are repeatedly linked to w/c ratio.

Yet its effect is not one-directional. Increasing w/c generally improves initial flowability and may reduce yield stress, but it also increases the amount of excess water available for bleeding and may weaken suspension coherence. Decreasing w/c may reduce bleeding and improve early body, but it can also reduce injectability and increase risk of filtration, especially as hydration progresses. Therefore, w/c ratio should be treated in the tool as a governing lever that must be balanced against target property ranges rather than optimized in isolation.

2.7.2 Cement fineness and cement type

Cement fineness influences both geometry and chemistry. In theory, smaller particles should improve access to small constrictions. In practice, the literature shows an optimum rather than a monotonic trend. Håkansson, U. (1993) reported increases in both yield stress and plastic viscosity with increasing specific surface, while Draganović, A., and Stille, H. (2011) demonstrated poorer penetrability in some very fine cements due to hydration and flocculation effects. Consequently, cement type should be treated as a structural variable in the database, not as a simple 'finer is better' ranking. This is directly relevant to the user's planned comparison between INJ30 and UF20.

2.7.3 Superplasticizers, flow agents, and viscosity-modifiers

The literature consistently shows that admixtures can improve dispersion and lower apparent viscosity, but their effects are conditional on dosage, binder chemistry, and time. Mohammed, M. (2014) showed that talc-containing systems could exhibit lower yield stress and more Newtonian-like behavior than palygorskite-modified systems, while Song, W. (2025) showed strong sensitivity of grouting performance to HPMC dosage and to its interaction with water/cement ratio. In recent application-oriented studies, additives are often introduced to increase anti-dispersion, shorten setting time, or improve early strength. However, the trade-offs remain significant. For example, strong viscosity modification may improve washout resistance but reduce injectability into fine fractures.

For the present thesis, this has a practical implication: the planned admixture combinations should not be analyzed purely by brand or supplier. Instead, the tool logic should evaluate whether an admixture system produces a consistent shift in property windows across different cements and w/c ratios. If an admixture works well only within a narrow compositional region, the tool should reflect that through conditional recommendations rather than broad generalization.

2.8 Measurement methods relevant to the present thesis

The reviewed literature supports a hierarchy of testing methods, each with its own role. Rotational rheometers provide the most direct route to yield stress and plastic viscosity, but the chosen geometry, shear protocol, and fitting range matter. Marsh funnels, flow cones, and mini-slump devices are practical screening tools, but they compress rheological behavior into one simplified index. Penetrability and filtration devices are more application-relevant for injection grouting but are harder to standardize. Ultrasound-based in-line rheometry (UVP+PD) offers an important research bridge because it allows direct observation of velocity profiles during flow and can capture changes in rheology with time under flowing conditions.

Rahman, M. (2015) UVP+PD work is especially significant for future tool development because it points toward continuous monitoring rather than discrete batch testing. Although such equipment is not part of the current thesis workflow, its conceptual contribution is important: injection grout properties during actual pumping may differ from properties measured after sampling and transport to a laboratory rheometer. In the longer term, a mature proportioning tool could potentially be combined with in-line monitoring, allowing recipe selection and process control to interact.

The present thesis, however, is correctly positioned at an earlier stage. Before real-time optimization can be attempted, a robust database of mix–property relationships is needed. The literature therefore supports the chosen experimental strategy: systematic laboratory testing of rheology at defined times, filtration-related behavior, water separation, density, air content, and setting.

2.9 Existing mix-design approaches and their limitations

Relatively few publications present explicit mix-design methods for cement-based grout. Satyarno, I. (2014) proposed a practical method based on empirical equations and flow-cone results, intended to simplify the selection of cement–sand–water proportions. This contribution is useful as evidence that grout proportioning can be systematized rather than treated entirely as trial-and-error. However, the method is mainly oriented towards flowability and strength, including sand-containing systems, and is not tailored to micro-cement permeation grouting in narrow rock fractures. Its direct applicability to the present thesis is therefore limited.

Similarly, recent optimization studies often use orthogonal experimental designs or sensitivity analysis to identify influential factors in a specific grout system. These approaches are methodologically valuable because they reveal interactions and trade-offs, but they usually stop at identifying an optimal formulation for one application. They rarely produce a transferable decision-support framework that can recommend candidate recipes from a larger database based on user-defined property targets. This is precisely the niche of the present thesis.

In other words, the literature contains many pieces of the puzzle: rheological theory, filtration and penetrability testing, empirical proportioning, sensitivity analysis, and application-specific optimization, but very few attempts to integrate them into a practical selection tool for injection grout. That integration challenge is not trivial, because the selected output must balance conflicting indicators and translate them into recommendations that are understandable for end users.

2.10 Implications for the present study

The reviewed literature suggested several design principles for the present thesis project. First, recipe recommendations should be multi-criteria, not single-criteria. Second, 5 min and 20 min rheological values should be treated as distinct descriptors of the working window and structural development. Third, filtration-related tests should carry strong decision weight for rock injection applications. Fourth, water separation and setting results should be interpreted as screening variables that define acceptable regions rather than exact field predictors. Fifth, any final recommendation tool should be transparent about its logic, so that users can understand why a given recipe is shortlisted.

These implications guided the experimental program, the interpretation of results, and the development of the proportioning tool. The literature does not yet offer a complete blueprint for such a tool, but it provides a sufficiently strong theoretical foundation to justify the selected variables and to shape the decision logic.

3 Theoretical Framework

3.1 Injection grouting in hard rock tunnelling

In hard rock tunneling, injection grouting is typically conducted as part of a sequential excavation cycle. Boreholes are drilled radially ahead of the tunnel face, packers are installed to isolate injection zones, and injection grout is injected under controlled pressure to seal discontinuities. The effectiveness of this process depends not only on injection pressure and borehole pattern but also fundamentally on grout material properties. The grout must exhibit sufficient fluidity to penetrate fine fractures yet maintain stability to avoid bleeding and particle filtration that would block flow paths, see Figure 3.1.

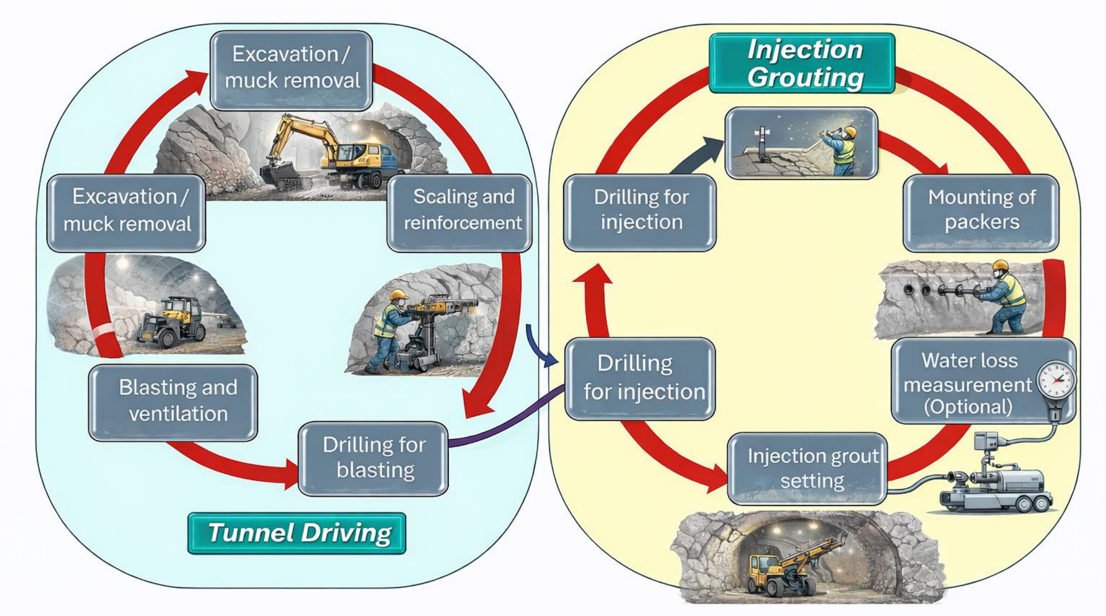

Figure 3.1 *Simplified schematic of pre-injection grouting ahead of the next tunnel excavation face.*

3.2 Injection grout mixing and basic equipment on site

In practical tunnel grouting operations, grout performance depends not only on material composition but also on mixing efficiency and injection equipment. High-quality dispersion of cement particles is essential to achieve stable rheological behavior and prevent premature flocculation or segregation. In industrial practice, colloidal mixers or high-shear mixers are commonly used to ensure uniform particle distribution and optimal activation of chemical admixtures.

Figure 3.2 Colloidal mixer in tunnel injection grouting.

After mixing, grout is typically stored in an agitator tank to prevent sedimentation and maintain homogeneity prior to pumping. Injections are carried out using piston or plunger pumps capable of delivering controlled pressure and flow rate.

Figure 3.3 Agitator in tunnel injection grouting.

Figure 3.4 Piston pump in tunnel injection grouting.

Packers are installed in pre-drilled boreholes to isolate injection zones and ensure effective penetration into fractures. Filtration behavior and penetrability are directly influenced by both grout rheology and pumping conditions.

Figure 3.5 Packers (Manschetter) in tunnel injection grouting.

Understanding the interaction between laboratory mixing procedures and field-scale equipment is essential to ensure that experimentally derived performance parameters are representative of practical applications.

3.3 Rheological behaviour of injection grouts

Cement-based grouts are commonly modeled as Bingham-type fluids, characterized by a yield stress and a plastic viscosity. Yield stress represents the minimum shear stress required to initiate flow, while plastic viscosity defines the resistance to flow once movement has started. Both parameters strongly influence pumpability and penetration capacity. Previous studies (Broberg et al., 2014; Mohammed et al., 2013) have focused on rheological characterization, but limited work integrates these parameters into practical mix design tools. Rheological parameters were determined by shear stress versus shear rate data through a rheometer using the Bingham model, Figure 3.6.

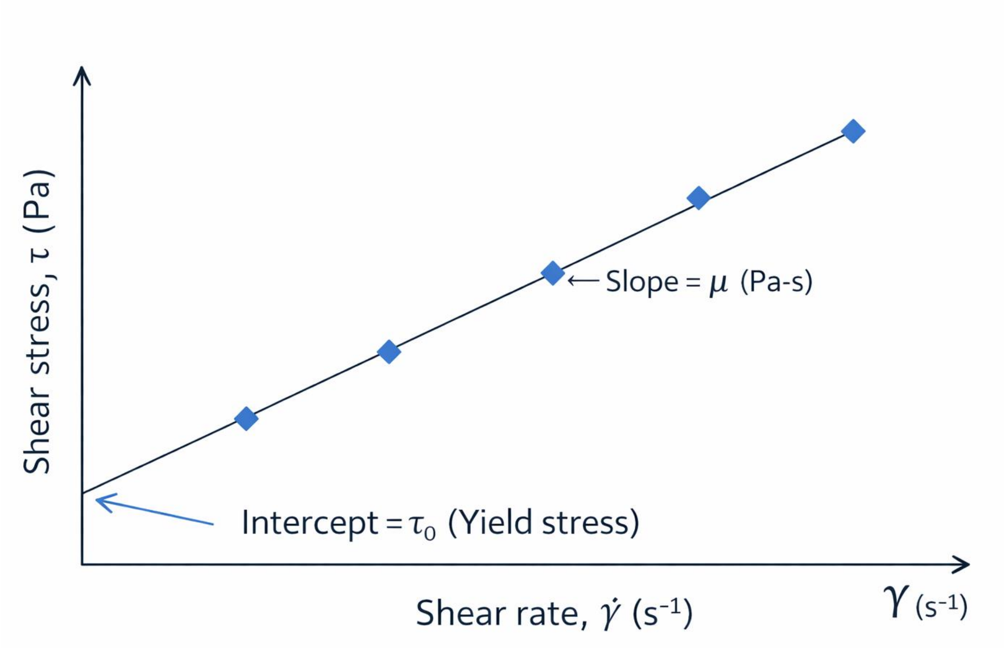

Figure 3.6 Idealized Bingham model illustrating the relationship between shear stress (τ) and shear rate ($\dot{\gamma}$).

As illustrated in Figure 2.1, the Bingham model assumes a linear relationship between shear stress and shear rate. The intercept of the linear fit corresponds to the yield stress (τ_0), which represents the minimum shear stress required to initiate flow. The slope of the line represents the plastic viscosity (μ), which describes the resistance to flow once yielding has occurred.

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{3.1}$$

where τ is the shear stress (Pa), τ_0 is the yield stress (Pa), μ is the plastic viscosity (Pa·s), and $\dot{\gamma}$ is the shear rate (s^{-1}). In the present study, yield stress and plastic viscosity were obtained by linear regression of measured shear stress versus shear rate data using the Bingham model.

The water–cement ratio is a primary determinant of rheological behavior. Lower water contents generally increase interparticle interactions and structural build-up, resulting in higher yield stress and viscosity. Chemical admixtures, particularly superplasticizers and accelerators, further modify rheology through dispersion mechanisms and hydration kinetics. Early-age rheology, typically within the first 5–20 minutes after mixing, is especially critical in tunneling operations, where injection must occur within limited time windows.

3.4 Stability and water separation

Water separation, often referred to as bleeding, reflects the stability of the grout suspension. Excessive bleeding may lead to segregation, reduced homogeneity, and weakened sealing performance in fine fractures. Stability is governed by particle size distribution, solid concentration, admixture type, and interaction between cement particles and chemical additives. A well-designed grout should maintain a stable particle network that minimizes free water migration during the conditioning period.

3.5 Setting behaviour

Setting time determines the operational window available for injection and subsequent excavation activities. Accelerators are commonly used to reduce setting time in order to improve productivity and reduce waiting periods. However, overdosing may result in rapid stiffening and loss of pumpability, whereas insufficient dosage may delay structural gain and prolong project timelines. Therefore, a balance must be achieved between workability retention and controlled stiffening.

3.6 Filtration and Penetrability

Filtration performance represents the ability of grout to pass through narrow apertures without excessive particle retention. Even when fine micro cements are used, inappropriate rheology or instability may lead to clogging at fracture entrances. Filtration is therefore a coupled phenomenon involving particle size, dispersion efficiency, viscosity, yield stress, and air content. Understanding these interactions is essential for predicting field performance in fine-fracture systems.

4 Materials and Methods

The experimental program was designed in accordance with the methodology defined during the planning stage, and during implementation, modifications were made as per discussions with representatives from admixture companies, based on initial results.

Although three micro cements are manufactured by Heidelberg Materials Sverige, two micro cements were selected for the investigation based on market demand and availability: Injektering 30 (INJ30) and Ultrafine 20 (UF20). These materials differ primarily in particle size distribution and fineness.

Table 4.1 Micro cement parameters.

Parameter	Injektering 30 (Inj30)	Ultrafine 20 (UF20)	Ultrafine 12 (UF12)	Requirements in EN 197–1
Cement, density [kg/m^3]	3100–3200	3100–3200	3100–3200	
Bulk density (kg/m^3)	900 ± 200	800 ± 200	700 ± 200	
Specific surface (m^2/kg, BET1)	1355	2040	2200	
PSD, d95 (μm)	≤ 30	≤ 20	≤ 12	
Alkali, Na_2Oekv (%)	0,55 ± 0,05	0,55 ± 0,05	0,55 ± 0,05	≤ 0,6 (According to SS134203)
Sulfates, SO_3 (%)	2,8 ± 0,2	2,8 ± 0,2	2,8 ± 0,2	≤ 3,0
C_3A (%)	2,0 ± 0,7	2,0 ± 0,7	2,0 ± 0,7	≤ 3
Chloride, Cl^- (%)	0,02 ± 0,01	0,02 ± 0,01	0,02 ± 0,01	≤ 0,10
Water-soluble chromium Cr^{6+} (PPM)	0–2	0–2	0–2	≤ 2 (Clause 47 of Annex XVII of the REACH Regulations)

Each cement was tested across selected water–cement ratios and combined with admixture systems supplied by three manufacturers. Accelerators included Mapefast SA, Sika iAcc-1, and Normet Tamcem SA, while superplasticizers included Mapei Grout Tech System N (M GTSN), Sika iFlow-1, and Normet Tamcem SP-I. To maintain industrial relevance, admixtures were combined only within the same supplier system.

Table 4.2 Experimental matrix showing tested combinations of cement type, water–cement ratio, and admixture systems.

Cement Type	w/c	Accelerator Type	Accelerator Dosage (%)	Superplasticizer Type	SP Dosage (%)	Supplier
INJ30	0.8	Mapefast SA	1.0 – 2.0	Mapei GTSN	0.5 – 1.5	Mapei
INJ30	1.0	Mapefast SA	1.0 – 2.0	Mapei GTSN	0.5 – 1.5	Mapei
INJ30	0.8	Sika iAcc-1	1.0 – 2.0	Sika iFlow-1	0.3 – 0.5	Sika
INJ30	1.0	Sika iAcc-1	1.0 – 2.0	Sika iFlow-1	0.3 – 0.5	Sika
INJ30	0.8	Tamcem SA	2.0 – 4.0	Tamcem SP-I	0.5 – 1.0	Normet
INJ30	1.0	Tamcem SA	2.0 – 4.0	Tamcem SP-I	0.5 – 1.0	Normet
UF20	1.0	Same three systems	Same ranges	Same matching SP	Same ranges	Same supplier rule
UF20	1.2	Same three systems	Same ranges	Same matching SP	Same ranges	Same supplier rule

The matrix was designed to isolate the effects of cement fineness, water–cement ratio, and admixture chemistry while maintaining industrially realistic combinations.

The mixing protocol was standardized to ensure reproducibility. Each injection grout was first dispersed in a conventional mixer for uniform blending, followed by high-shear dispersion to achieve the required particle distribution and fresh-state characteristics. Rheological measurements were performed at 5 and 20 minutes after mixing using a rotational viscometer, and yield stress and plastic viscosity were calculated using the Bingham model.

Water separation was determined after three hours of conditioning at a controlled temperature. Setting time was evaluated using a fall cone method under low-temperature conditions representative of underground environments. Filtration performance was assessed using a manual filter pump equipped with standardized mesh filters. Density was measured volumetrically, and air content was calculated by comparing the measured density with the theoretical solid density.

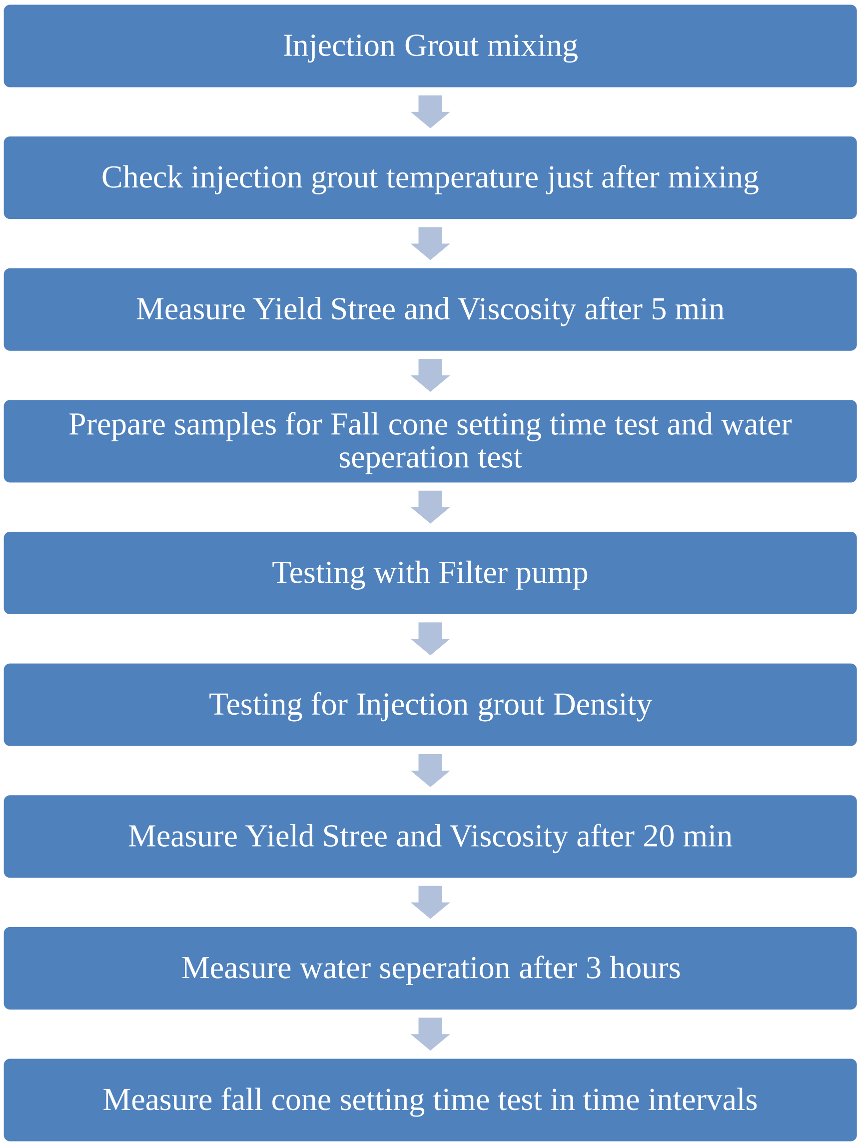

Figure 4.1 Standardized mixing and testing procedure for each grout batch.

The experimental matrix was structured to systematically isolate the effects of water–cement ratio, cement type, accelerator dosage, and superplasticizer dosage.

4.1 Experimental scope and limitations

- Focus on fresh-state performance only.
- Two Micro-cements from Heidelberg Materials Cement Sverige.
- Limited curing time window.
- Three Accelerators and three superplasticizers.
- Field validation and hardened properties excluded.
- Tool limited to tested materials and lab conditions.

5 Results and Analysis

This chapter presents a critical analysis of the fresh-state behaviour of the investigated injection grout systems. The analysis is based on the measured rheological parameters, water separation, setting behaviour, calculated air content, and filtration performance for two micro-cement systems, INJ30 and UF20. For INJ30, the investigated water-cement ratios were 0.8 and 1.0, while UF20 was evaluated at water-cement ratios of 1.0 and 1.2. The discussion focuses on how water-cement ratio, accelerator dosage, and flow-agent dosage influence the balance between injectability, pumpability, stability, and early-age structuration.

The results are interpreted using the concept that an injection grout should not be optimized for a single property only. A grout with very low yield stress and low viscosity may appear highly injectable, but may also be vulnerable to bleeding, segregation, and poor material build-up after placement. Conversely, a grout with high yield stress and high viscosity may be stable but difficult to pump and may show limited penetration into fine fractures. Therefore, the final assessment is based on the combined performance of rheology, filtration, water separation, setting time, and air content.

5.1 Overview of measured property ranges

Table 5.1 summarizes the measured ranges for the two cement systems. The values show that INJ30 produced a wider rheological response than UF20 within the tested matrix. This is partly related to the lower water-cement ratio used for INJ30 and partly to the sensitivity of some INJ30 mixtures to accelerator-dominated early structuration. UF20, although finer than INJ30, was tested at higher water-cement ratios and therefore generally showed lower yield stress and lower plastic viscosity values.

Table 5.1 Summary of measured fresh-state property ranges for INJ30 and UF20 grout mixtures.

Property	INJ30 range	UF20 range	Main interpretation
Yield stress at 5 min	0.036-13.05 Pa	0.019-3.475 Pa	INJ30 showed stronger early structuration, especially at w/c = 0.8 and in accelerator-rich mixtures.
Yield stress at 20 min	0.093-13.72 Pa	0.166-4.483 Pa	Most mixes stiffened with time, but some flow-agent-rich mixtures remained very low in yield stress.
Plastic viscosity at 5 min	3.765-39.85 mPa.s	3.248-18.90 mPa.s	Lower w/c and accelerator addition increased flow resistance.
Plastic viscosity at 20 min	5.995-48.00 mPa.s	4.922-18.07 mPa.s	Time-dependent viscosity increase indicates hydration and flocculation.
Water separation after 3 h	0-7.881 vol.%	0-6.51 vol.%	Higher w/c generally increased bleeding tendency, especially for UF20 at w/c = 1.2.

Fall cone setting time test	2.717-9.917 hrs	2.25-9.167 hrs	Accelerator dosage reduced setting time, while higher w/c and flow-agent-dominated systems delayed structuration.
Filtration volume	10-300 mL at 75 µm; failed mixes checked at 90 µm	100-300 mL at 45 µm; all passed 300 mL at 63 µm	Filtration depended on both particle size and early flocculation state, not only cement fineness.

5.2 Rheological behaviour of INJ30

5.2.1 Yield stress development

The INJ30 yield stress results show a clear dependence on water-cement ratio and admixture combination. At w/c = 0.8, most mixes had higher yield stress than the corresponding w/c = 1.0 mixtures. This is expected because a lower water-cement ratio increases the solid volume fraction, reduces interparticle spacing, and increases particle-particle interaction. In a Bingham-type grout, this appears as a higher stress requirement before flow begins.

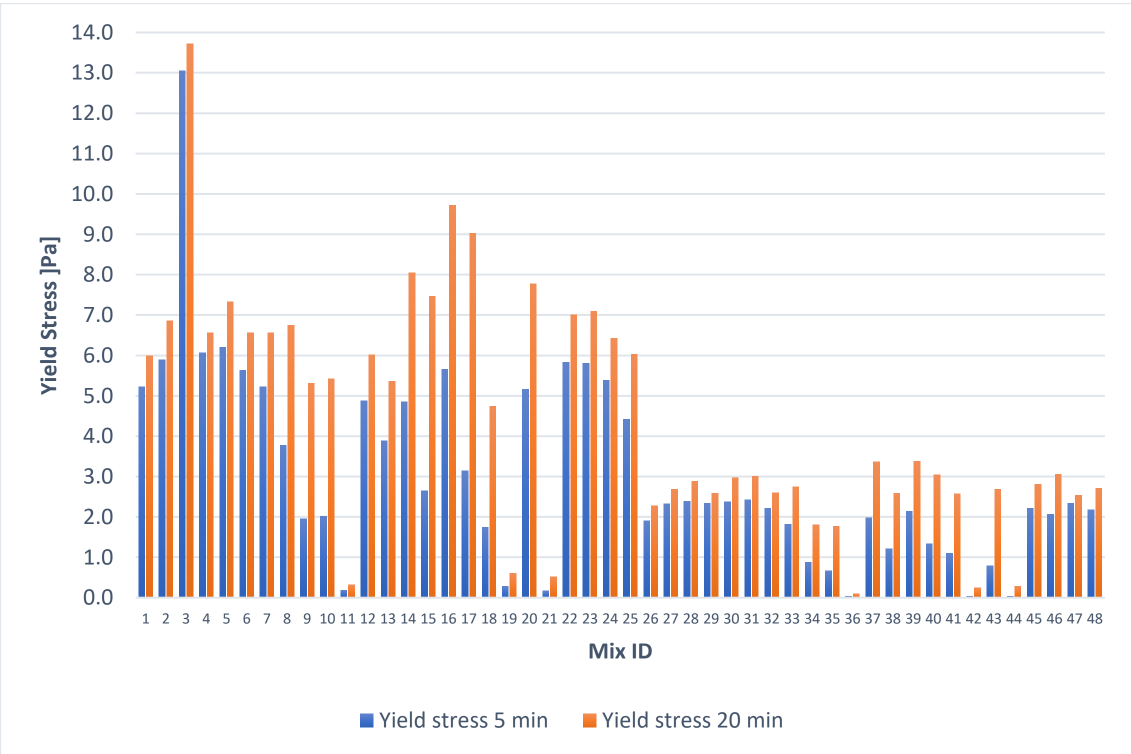

Figure 5.1 Yield stress at 5 and 20 minutes for INJ30.

The most critical behavior was observed in the low-w/c accelerator-rich region. Mix R3, corresponding to INJ30 at w/c = 0.8 with 2% Mapei accelerator and no flow agent, reached approximately 13.05 Pa at 5 minutes and 13.72 Pa at 20 minutes. This mix was not only the highest in yield stress but also showed limited additional increase between 5 and 20 minutes. This indicates that substantial structuration had already occurred by the first measurement point. In practice, such behavior is risky because the injection grout may begin to lose injectability almost immediately after mixing. If pumping or injection is delayed, the grout may require higher pressure, may block hoses or borehole restrictions, and may have poor penetration into fine fractures.

In contrast, several INJ30 mixes containing Sika flow agent at 0.5% showed extremely low yield stress values. Examples include R11, R19, R21, R36, R42, and R44, where the yield stress remained close to zero or very low even after 20 minutes. From an injectability point of view, such mixes appear favorable because a low yield stress reduces the pressure required to initiate flow. However, the practical risk is that the grout may become over-dispersed. When cement particles are strongly dispersed, and the material has insufficient internal structure, the grout may be more prone to water separation, particle settlement, and non-uniform properties after placement. Therefore, these mixtures should not be judged as superior based only on low yield stress.
The increase from 5 to 20 minutes was also important. For many INJ30 mixtures, yield stress increased moderately with time, which is consistent with early hydration, flocculation, and thixotropic build-up. This behavior is generally acceptable if the increase remains within the available working time. However, rapid increases are critical because injection grouting often depends on a limited time window between mixing, transport, pumping, and penetration into the fracture system. The results, therefore, show that the 20-minute value is more representative of field risk than the 5-minute value alone.

5.2.2 Plastic viscosity development

The plastic viscosity results for INJ30 followed the same general pattern as the yield stress results. At w/c = 0.8, plastic viscosity was generally higher than at w/c = 1.0. This reflects the increased resistance to flow after the yield stress has been exceeded. While yield stress controls the initiation of movement, plastic viscosity controls the resistance during continuous pumping and fracture flow. High viscosity can therefore increase pumping pressure and reduce the distance of grout spread.

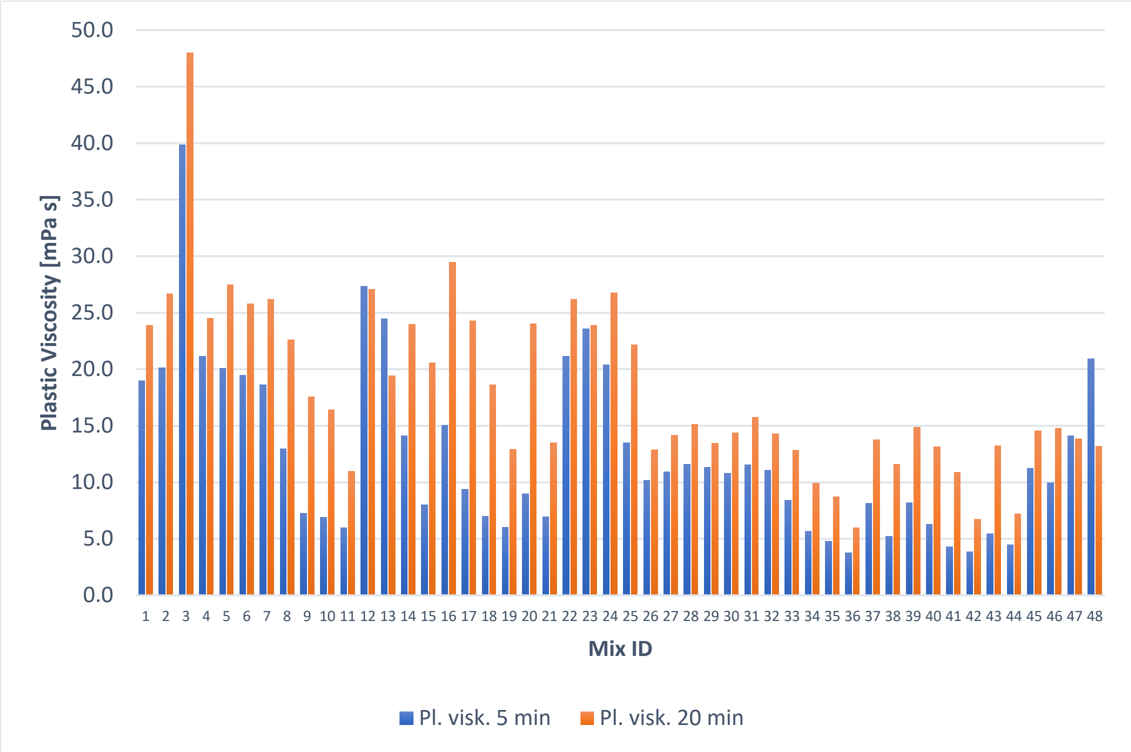

Figure 5.2 Plastic viscosity at 5 and 20 minutes for INJ30.

Mix R3 again represented the most critical behavior, with plastic viscosity increasing from approximately 39.85 mPa.s at 5 minutes to 48.00 mPa.s at 20 minutes. This confirms that the mix was not only stiff at the onset of flow but also highly resistant during continued flow. The combined high yield stress and high plastic viscosity indicate a mix with poor pumpability and high clogging risk. Such a mix may be useful only where very fast stiffening is required, and injection distances are short, but it is unsuitable for fine-fracture penetration or long-distance injections.

Several flow-agent-containing mixtures showed the opposite behavior, with low plastic viscosity even after 20 minutes. This indicates strong dispersion and good flowability. However, when low plastic viscosity is combined with very low yield stress, the injection grout may lack enough structure to resist segregation. Therefore, the preferred INJ30 performance window should be a moderate yield stress and moderate plastic viscosity, rather than the minimum possible values. The results confirm that a balanced rheological profile is more important than achieving maximum flowability.

5.3 Rheological behaviour of UF20

5.3.1 Yield stress development

The UF20 mixtures showed lower yield stress values than the INJ30 mixtures, despite UF20 being a finer micro-cement. This apparent contradiction is explained by the tested water-cement ratios. UF20 was tested at w/c = 1.0 and 1.2, whereas INJ30 included w/c = 0.8. The higher water content in the UF20 matrix reduced particle concentration and allowed easier particle movement, which lowered the yield stress. This demonstrates that cement fineness alone cannot explain grout rheology; the combined effect of water content, admixture type, and early hydration must be considered.

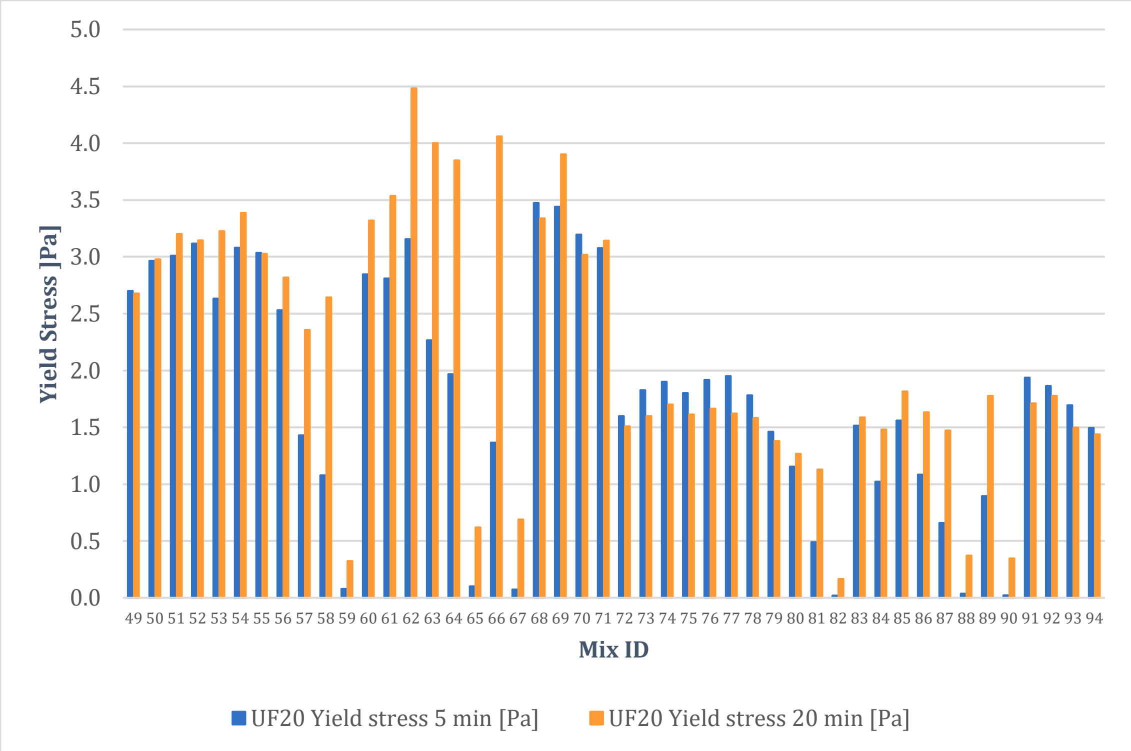

Figure 5.3 Yield stress at 5 and 20 minutes for UF20.

For UF20, the w/c = 1.0 mixes generally produced higher yield stress than the w/c = 1.2 mixes. This trend is technically expected because the denser suspension at w/c = 1.0 produces more particle contacts and greater resistance to flow initiation. At w/c = 1.2, the larger water volume reduces interparticle contact and weakens the early structure. This improves injectability but increases the risk of instability, particularly when the yield stress becomes very low.

A key observation was the large increase in yield stress from 5 to 20 minutes for some UF20 mixtures. For example, mixes in the region of R62-R67 showed clear time-dependent structuration, especially where the accelerator and flow agent were combined. This indicates that UF20 mixtures can remain relatively fluid at 5 minutes but develop measurable stiffness by 20 minutes. In practice, this may be favorable if the grout is pumped quickly after mixing, because it combines early injectability with later build-up. However, it also creates risk if the injection is delayed, because the field performance may differ significantly from the 5 minute laboratory value.

The low yield stress mixtures, especially those containing Sika flow agent at 0.5%, showed values close to zero at 5 minutes and still low values at 20 minutes. These mixes are likely to be highly pumpable, but their stability must be evaluated carefully. For injection grout, very low yield stress is not automatically beneficial, as mentioned with the INJ30 analysis also. It may indicate that the cement particles are too well dispersed to maintain suspension stability, particularly at a higher water-cement ratio.

5.3.2 Plastic viscosity development

The UF20 plastic viscosity results showed a clear distinction between w/c = 1.0 and w/c = 1.2. The w/c = 1.0 mixtures generally had higher plastic viscosity, reflecting a denser particle system and greater resistance during flow. The w/c = 1.2 mixtures were more fluid and therefore potentially more suitable for fine-fracture injection, provided that water separation and filtration results remain acceptable.

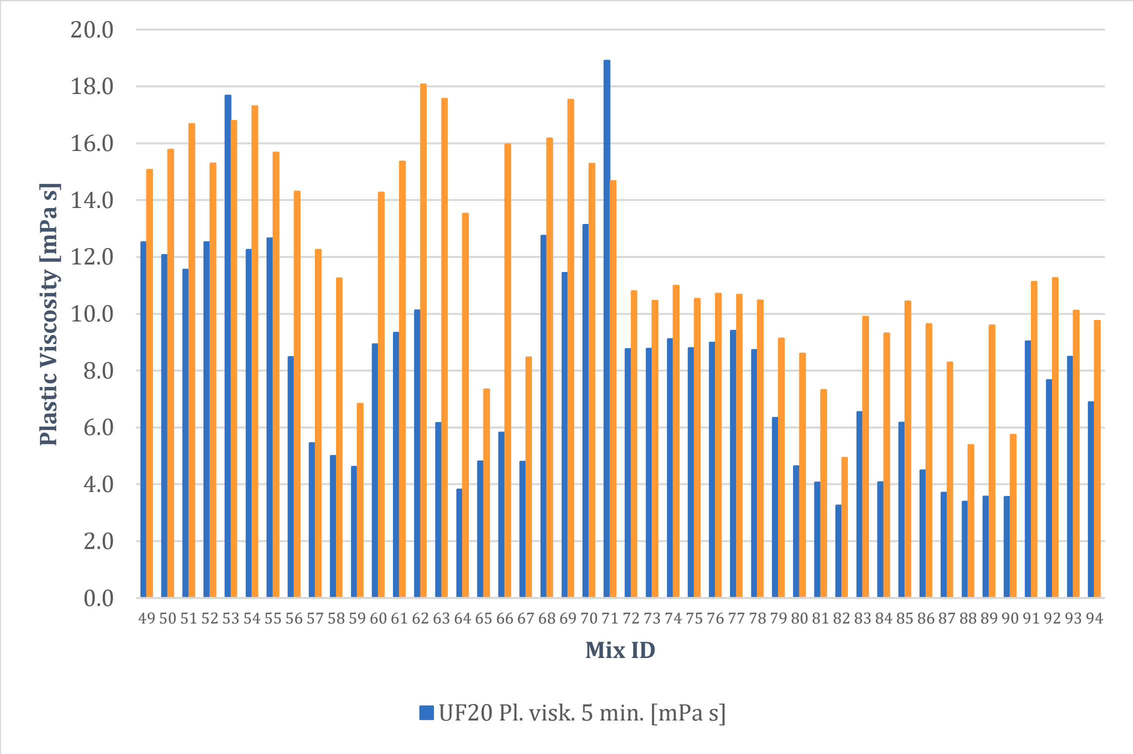

Figure 5.4 Plastic viscosity at 5 and 20 minutes for UF20.

Most UF20 mixtures increased in plastic viscosity between 5 and 20 minutes. This confirms ongoing time-dependent changes caused by cement hydration, particle flocculation, and possible interaction between accelerator and superplasticizer. The increase was generally less extreme than in the most critical INJ30 mixtures, indicating a broader working range for many UF20 combinations.

Overall, the UF20 rheology results show that the material can provide good injectability, especially at w/c = 1.2, but stability becomes the controlling limitation. This means that the UF20 mix design should be governed by a coupled criterion: the mix should be fluid enough to pass fine restrictions but structured enough to avoid bleeding and segregation.

5.4 Water separation and stability

Water separation after 3 hours was used as an indicator of bleeding and segregation tendency. Although a universal acceptance limit for injection grout was not identified, a practical reference value of 1 vol.% was used for evaluating stability. This limit should be interpreted as a project-specific control level rather than a fixed standard requirement.

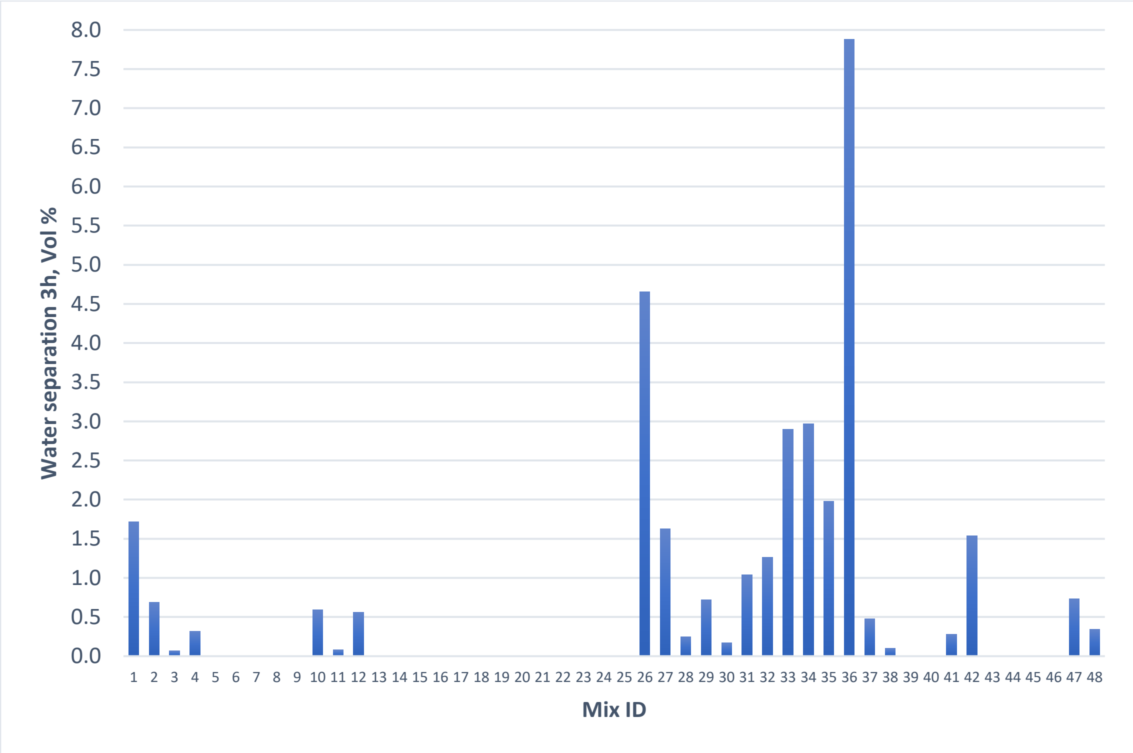

Figure 5.5 Water separation percentage after 3 hours for INJ30 mixtures.

For INJ30 at w/c = 0.8, most mixtures showed low or zero water separation. This confirms that the lower water content improved suspension stability. However, the reference INJ30 mixture at w/c = 0.8 showed 1.72 vol.% water separation, which indicates that a low water-cement ratio alone does not guarantee stability. Stability is also influenced by cement dispersion state, flocculation, and admixture compatibility. Some accelerator-rich mixes showed low separation because rapid structuration immobilized water, but this improvement came at the cost of higher yield stress and lower injectability.

For INJ30 at w/c = 1.0, the scatter in water separation increased. Several mixtures exceeded 1 vol.%, with the highest value reaching approximately 7.88 vol.%. This confirms the strong effect of increased water content on bleeding tendency. A higher water-cement ratio improves flowability but creates more free water in the suspension. If the particle network is not sufficiently stable, this water can separate during rest. Therefore, w/c = 1.0 INJ30 mixtures require careful admixture control to avoid over-dispersion and bleeding.

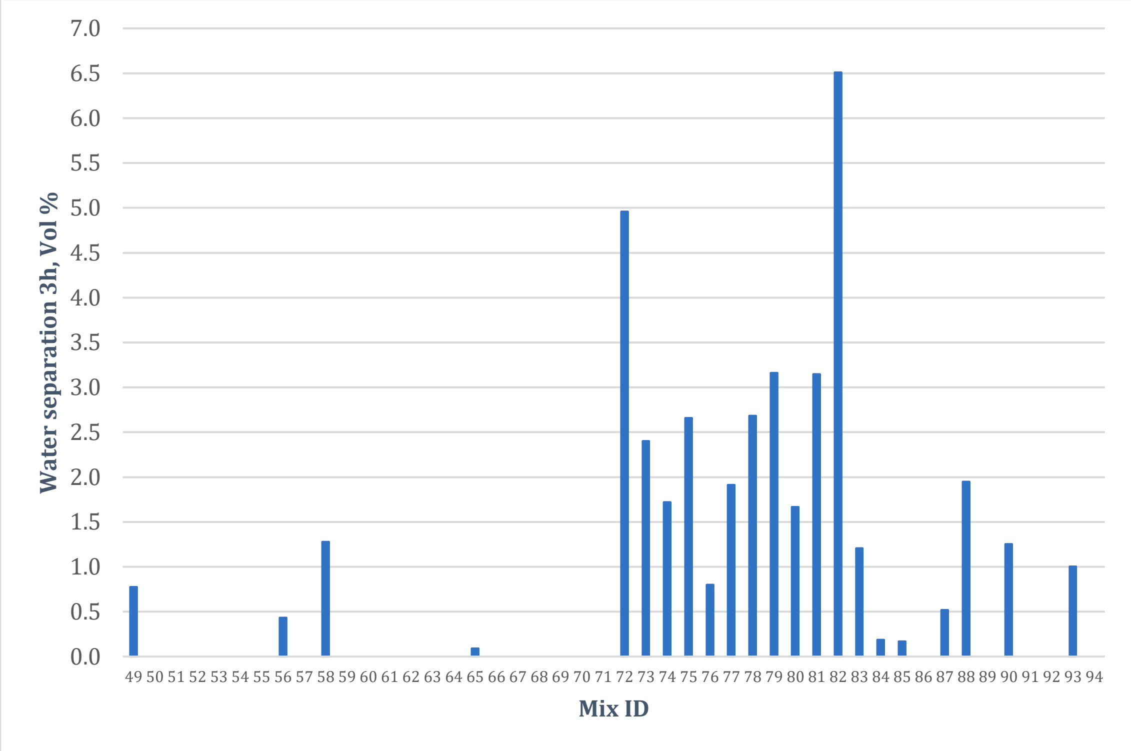

Figure 5.6 Water separation percentage after 3 hours for UF20 mixtures.

The UF20 water separation results showed a clearer water-cement ratio effect. At w/c = 1.0, most mixtures had low or negligible water separation. At w/c = 1.2, several mixtures exceeded the 1 vol.% reference level, with the highest result around 6.51 vol.%. This shows that increasing water content improved rheological flowability but reduced stability. The result is particularly important for UF20 because some w/c = 1.2 mixtures showed attractive rheology and good filtration performance, but the water separation results indicate a potential field risk.

From a practical perspective, water separation can reduce the quality of the placed injection grout. If water separates inside fractures, the remaining solids may become non-uniform, the effective sealing material may shrink or settle, and local channels may remain unsealed. Therefore, mixtures with high water separation should not be recommended even if they have low yield stress or good filter-pump passage.

5.5 Setting behaviour from fall cone test results

The fall-cone setting results describe the time required for the injection grout to reach a defined shear strength level. In practical injection grouting, setting time controls the working window, the risk of blockage during pumping, and the time required before the next construction operation. A very short setting time may improve early stability but increases the risk of pump blockage. A very long setting time improves handling and pumping flexibility but may delay sealing performance and reduce early resistance to wash-out.

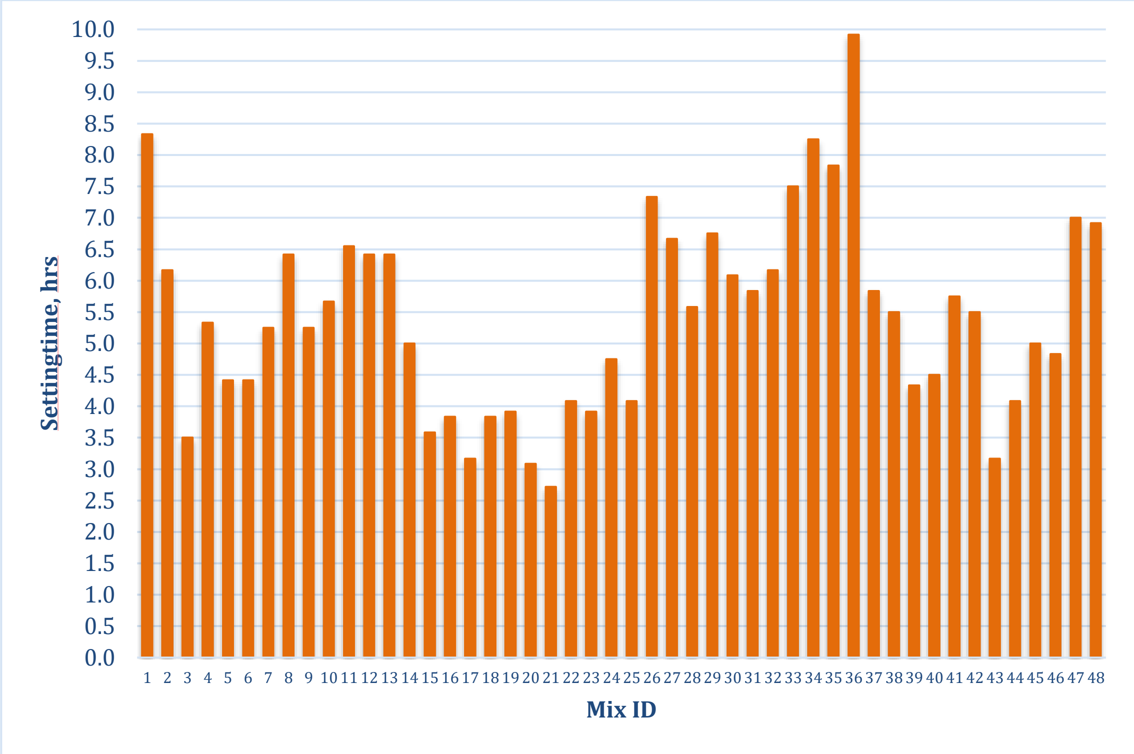

Figure 5.7 Fall cone setting time for INJ30 mixtures.

For INJ30, increasing the water-cement ratio from 0.8 to 1.0 generally increased the setting time. Several w/c = 1.0 mixes exceeded 7 hours, and one mix reached almost 10 hours. These were mainly mixtures without an accelerator and with flow-agent-dominated behaviour. This result is expected because higher water content increases the spacing between cement particles, reduces early particle contact, and delays the development of a continuous solid structure. Flow agents may further delay structuration by dispersing particles and reducing flocculation.

Accelerator dosage was the main factor reducing setting time. INJ30 mixtures with accelerator generally showed shorter setting times than the corresponding reference or flow-agent-only mixtures. However, the result must be interpreted together with rheology. A mixture that sets quickly may also show high yield stress and high plastic viscosity during the injection period. Therefore, accelerator dosage should be optimized to produce controlled early build-up rather than maximum acceleration.

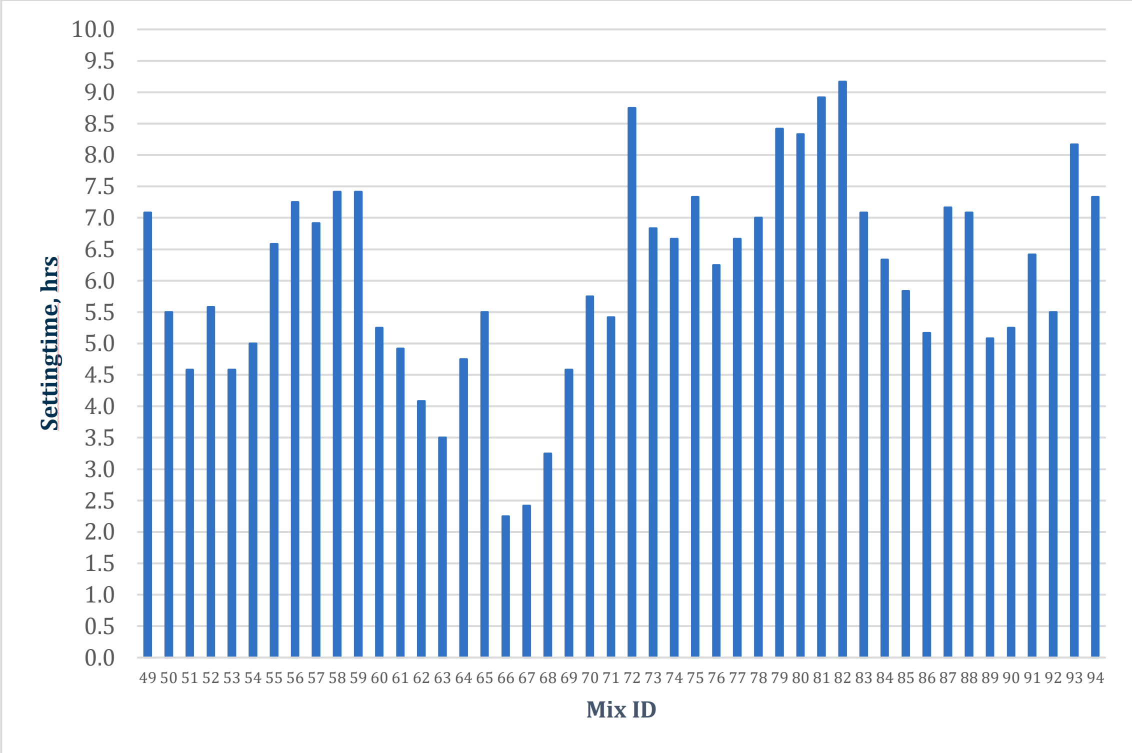

Figure 5.8 Fall cone setting time for UF20 mixtures.

For UF20, setting times ranged from approximately 2.25 to 9.17 hours. The shortest setting times occurred in accelerators containing mixtures, while higher water-cement ratios and some flow-agent combinations delayed setting. Similar to INJ30, this confirms that the setting response is governed by competition between acceleration, dilution, and dispersion. The UF20 results also show that some mixtures can combine low early rheology with later setting development, which may be useful for injection if the water separation remains controlled.

5.6 Calculated air content and density-related interpretation

Calculated air content was derived from measured density and theoretical density. A practical reference threshold of approximately 2% was used, based on industry practice for tunnel grouting. Low and controlled air content is desirable because excessive air can reduce effective density, influence pumpability, create compressibility during pumping, and reduce the continuity of the hardened injection grout in fractures.

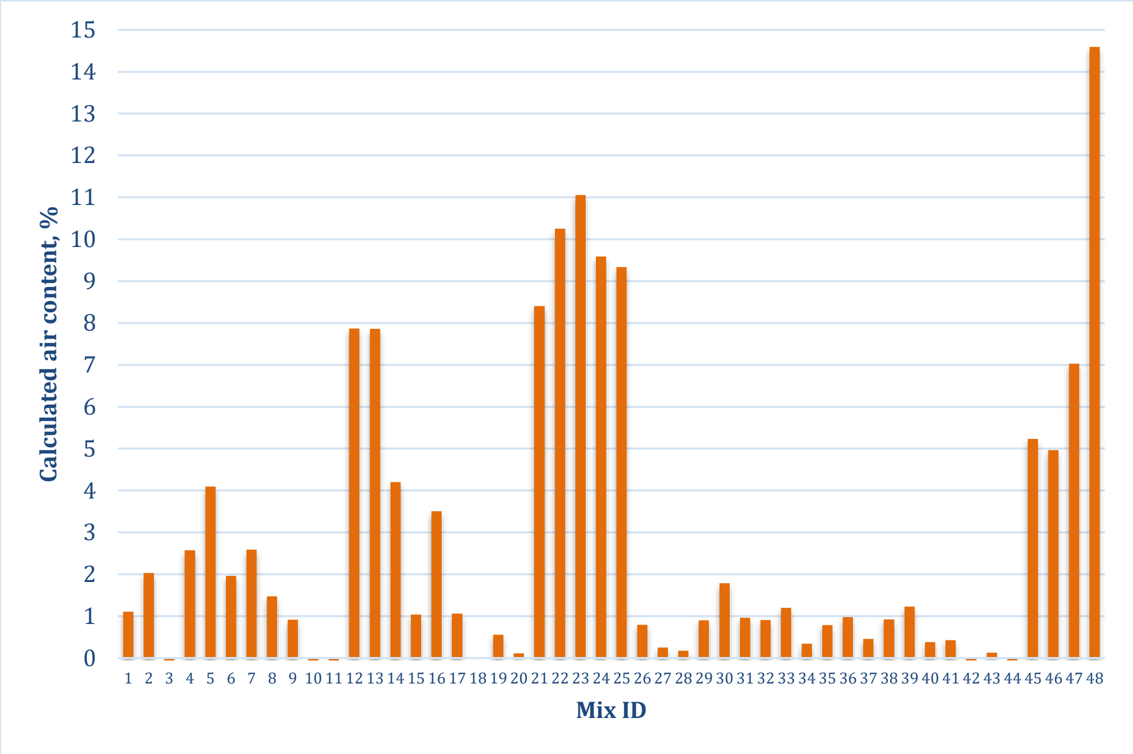

Figure 5.9 Calculated air content of grout mixtures for INJ30.

The INJ30 results showed that many mixtures were below or close to the 2% reference level, especially in the w/c = 1.0 group. However, some mixtures showed very high calculated air contents, above 7%, and in one case above 14%. These values are unlikely to represent only stable entrained air; they may also reflect foam formation, incomplete deaeration, density measurement sensitivity, or uncertainty in the assumed theoretical density. Nevertheless, they indicate that those mixtures should be treated cautiously because abnormal density behavior may affect the interpretation of other fresh-state properties.

Some INJ30 mixes showed slightly negative calculated air content. Negative air content is not physically meaningful and should be interpreted as an indication of measurement uncertainty rather than real material behavior. Possible reasons include weighing error, small differences in actual material density, incomplete correction for admixture density, or trapped solids distribution during sampling. For final interpretation, these values should be considered approximately zero.

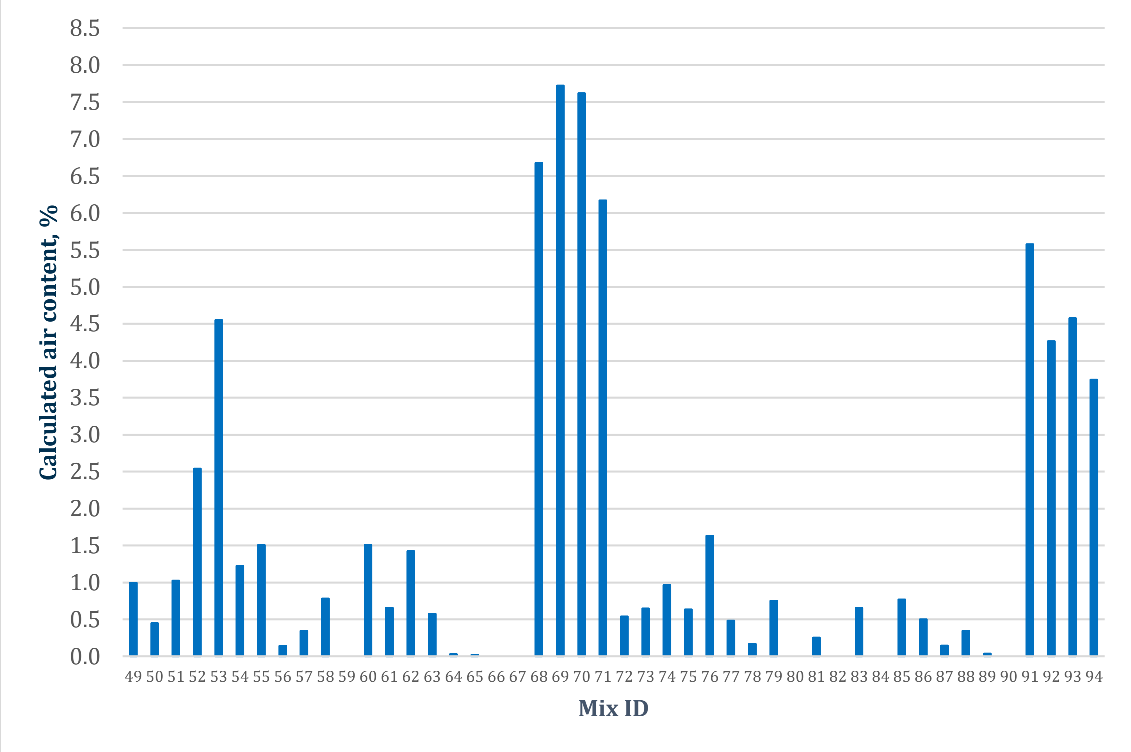

Figure 5.10 Calculated air content of grout mixtures for UF20.

The UF20 calculated air content was generally lower and more stable than the most critical INJ30 cases, although some mixtures still exceeded the 2% reference level. High air content was observed in selected mixes around R68-R71 and R91-R94. These mixtures should be evaluated carefully in combination with rheology and water separation. If high air content occurs together with low viscosity, it may indicate unstable foaming or sensitivity to the mixing procedure.

5.7 Filtration performance and penetrability

The filter-pump test was used to evaluate the ability of the injection grout to pass through fine restrictions and to identify potential clogging tendency. Filtration performance is directly relevant to injection grouting because the grout must penetrate fractures without forming a filter cake or particle plug at constrictions. However, filtration performance is not controlled by particle size alone. It is also influenced by flocculation, hydration, yield stress, plastic viscosity, and admixture compatibility.

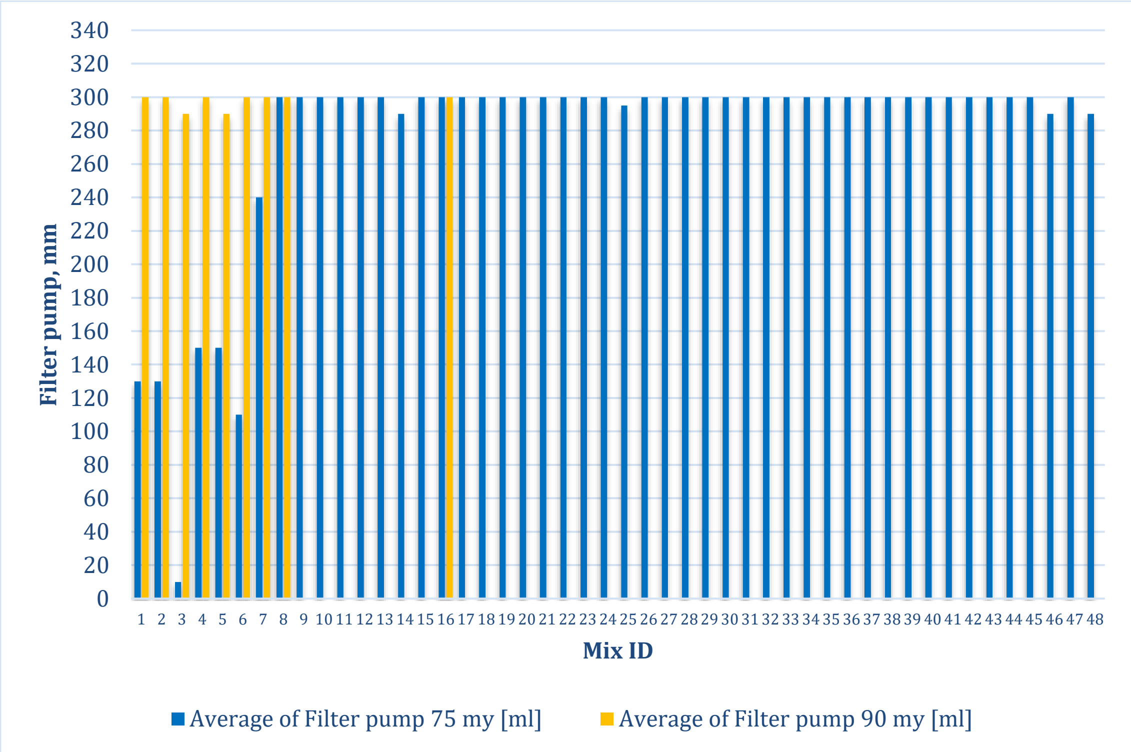

Figure 5.11 Filtration volume for INJ30.

For INJ30, most mixtures passed the full 300 mL through the 75 micrometer mesh, indicating acceptable filtration performance. The main exceptions occurred in the low-w/c, accelerator-rich region. Mixes R1-R7 showed reduced filtration volumes at 75 micrometer, and R3 showed an extremely low value of approximately 10 mL. This is consistent with its high yield stress and high plastic viscosity. The poor filtration result suggests that the mix formed a stiff or flocculated structure that blocked the mesh quickly. Although the cement particle size may be compatible with the sieve size, the effective particle clusters or early-formed structures were too large or too resistant to pass.

When the critical INJ30 mixtures were checked at 90 micrometers, the filtration volume increased strongly, and most passed close to 300 mL. This confirms that the blockage at 75 micrometers was a restriction-sensitivity issue rather than a complete loss of flowability. In field terms, such mixes may still penetrate larger fractures but are unsuitable for finer apertures. Therefore, the filter-pump result should be used as a classification tool for expected fracture aperture suitability.

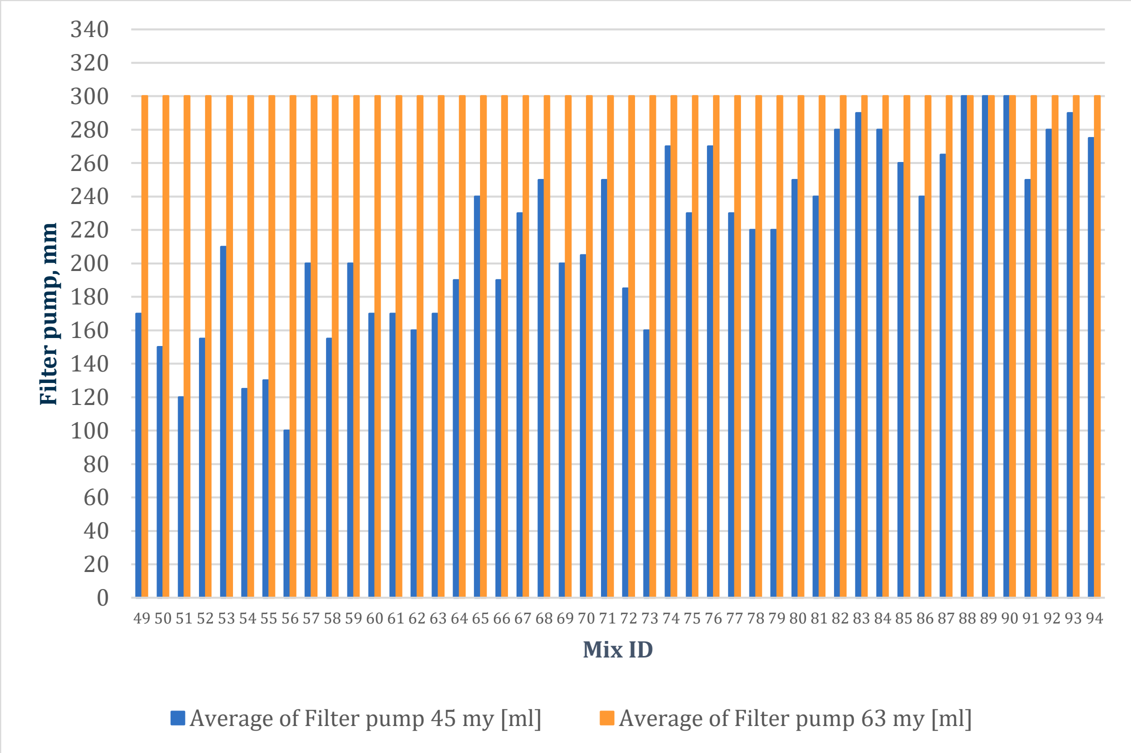

Figure 5.12 Filtration volume for UF20.

For UF20, the test was more demanding because the 45-micrometer mesh was used. Filtration volumes at 45 micrometer varied from about 100 to 300 mL, while all mixtures passed 300 mL through the 63 micrometer mesh. This shows that UF20 generally has good penetrability at the 63 micrometer level but becomes more sensitive at 45 micrometer. The best results at 45 micrometer were observed in the more fluid and well-dispersed mixtures, especially several w/c = 1.2 combinations. However, these mixes must again be checked against water separation, because excellent filtration can coincide with insufficient stability.

Overall, the filtration results demonstrate the central trade-off in injection grout design. Increasing dispersion and water content improve passage through fine restrictions, but it may increase bleeding risk. Increasing accelerator dosage and reducing water content improve stability and setting, but it may reduce penetrability. The best injection grout should therefore be selected using multiple fresh-state criteria rather than filtration alone.

5.8 Cross-property assessment of performance windows

The combined results show that no single parameter is sufficient for injection grout selection. The most stable mixtures are not always the most injectable, and the most injectable mixtures are not always stable. This confirms the need for a performance-window approach. A suitable injection grout should satisfy minimum requirements for filtration and water separation while maintaining rheological values that are neither too low nor too high.

For INJ30, w/c = 0.8 generally improved stability but increased rheological resistance. Accelerator-only mixtures, especially high-dosage accelerator mixtures, produced excessive early structuration and poor filtration. In contrast, flow-agent-rich mixtures produced very low yield stress and low viscosity, but may be vulnerable to segregation. Therefore, the most promising INJ30 region is expected to be mixtures with moderate flow-agent dosage and controlled accelerator dosage, where yield stress and viscosity remain within a workable range and filtration remains close to 300 mL at 75 micrometer.

For UF20, w/c = 1.0 generally produced better stability, while w/c = 1.2 improved injectability and filtration. The main limitation of w/c = 1.2 was increased water separation. Therefore, UF20 mix selection should prioritize w/c = 1.0 when stability is the main requirement, and w/c = 1.2 only when fine-fracture penetration is critical, and water separation remains below the selected control limit. The best UF20 mixtures are those that combine acceptable 45 micrometer filtration with low water separation and moderate time-dependent rheology.

5.9 Unexpected and critical behaviours

Several behaviors require special attention. First, the high yield stress, high viscosity, and poor filtration of INJ30 R3 indicate that accelerator dosage can dominate the behavior of the injection grout, especially at a low water-cement ratio. This mix shows that rapid early structuration is not always beneficial; it can reduce the available working time and create clogging risk before the grout reaches the target fracture network.

Second, some Sika-flow-agent mixtures produced near-zero yield stress. While this indicates excellent dispersion, it may also mean that the grout has insufficient internal structure to resist particle settlement and water separation. Such mixtures should not be recommended without checking water separation and density stability.

Third, the UF20 results show that finer cement does not automatically produce higher measured yield stress or viscosity. The higher water-cement ratios used for UF20 reduced the overall rheological level. This confirms that comparisons between cement types must account for the complete mixture composition, not cement fineness alone.
Fourth, the calculated air content results include non-physical negative values and some very high values. These should be interpreted critically. Negative values should be treated as approximately zero and linked to measurement uncertainty. Very high values should be flagged as potential issues related to foaming, sampling, or density calculation assumptions.

Finally, some mixtures performed well in one test but poorly in another. For example, several highly fluid mixtures showed good filtration but increased bleeding risk, while several stable accelerator-rich mixtures showed poor filtration. This confirms that injection grout performance is a multi-objective problem and supports the development of a proportioning tool based on combined fresh-state criteria.

5.10 Development and demonstration of the proportioning tool

The experimental results were used as the database for developing an Excel-based injection grout mix proportioning tool. The role of the tool is to translate the experimental database into a practical decision-support system. Instead of selecting injection grout recipes only from experience or single-property targets, the tool allows the user to define target performance ranges for several fresh-state properties and then identifies the mixtures that best match those requirements.

The tool concept is based on three main elements: material selection, performance filtering, and match scoring. First, the user selects the micro cement type and admixture supplier or system when required. Second, the user should select the required parameters that are more demanding for the user's application. Third, the user defines target ranges for key parameters selected previously, such as yield stress, plastic viscosity, water separation, filtration volume, setting time, and air content. Finally, the tool searches the experimental database and ranks the mixtures according to how well they match the selected performance criteria.

The results analysis directly supports the tool logic. The rheology results define the working range for pumpability and injectability; the water separation results define stability limits; the setting-time results define the practical working window; the filtration results define the expected penetrability; and the air-content results provide a density and quality-control check. By combining these parameters, the tool reflects the actual trade-offs observed experimentally.

5.11 Research Questions Assessment

Based on the results obtained for INJ30 and UF20, the research questions can be assessed as follows.

RQ1 – How do water–cement ratios and admixture dosages affect the yield stress and plastic viscosity of injection grout?

The results show that the water–cement ratio strongly controls the baseline rheology of the injection grout. Lower w/c ratios generally produced higher yield stress and plastic viscosity due to increased particle concentration and stronger particle interaction. This was observed for both INJ30 and UF20. Admixture dosage also had a strong effect, especially between 5 and 20 minutes after mixing. Accelerator-rich mixes showed faster structuration and higher rheological values, while mixes with higher superplasticizer dosage showed reduced yield stress and viscosity. Therefore, rheology is governed by the combined effect of water content, admixture type, dosage, and time after mixing.

RQ2 – How do admixture combinations influence the setting time and water separation stability of injection grout?

The results indicate that accelerator dosage is the main factor controlling setting time, while water separation is affected by both water–cement ratio and admixture balance. Higher w/c ratios generally increased setting time and bleeding tendency. Lower w/c ratios showed better stability but sometimes higher rheological resistance. Superplasticizer improved flowability, but excessive dispersion could increase segregation risk. Therefore, a balanced accelerator–superplasticizer combination is required to achieve suitable workability, controlled setting, and low water separation.

RQ3 – How do micro-cement type and grout composition influence filtration performance in the Filter Pump Test?

The filter pump results show that filtration performance is influenced by both cement fineness and fresh-state behavior. INJ30 generally showed good filtration through the 75 µm mesh, although some low w/c and accelerator-rich mixes showed reduced filtrated volume. UF20 showed complete filtration through the 63 µm mesh, while the 45 µm mesh was more useful for differentiating between mixes. The results confirm that filtration is not governed by particle size alone, but also by rheology, dispersion, flocculation, and stability.

RQ4 – How can experimental findings be translated into design guidelines or a mix proportioning tool to predict fresh injection grout performance?

The experimental results provide a basis for defining performance windows for key fresh-state properties, including yield stress, plastic viscosity, water separation, filtration volume, setting time, density, and air content. These performance windows were used to develop an Excel-based grout mix proportioning tool. The tool compares user-defined target criteria with the experimental database and recommends suitable grout mixtures. This demonstrates that the experimental findings can be translated into a practical decision-support tool for performance-based grout mix selection.

6 Conclusion

This thesis investigated the fresh-state performance of cement-based injection grouts and developed a performance-based approach for injection grout mix selection. The study focused on INJ30 and UF20 micro-cement systems with different water–cement ratios, accelerator dosages, and superplasticizer dosages. The experimental program evaluated rheology, water separation, filtration performance, setting time, density, and calculated air content as key parameters for injection grout performance.

The results showed that injection grout behavior is governed by the combined effect of water–cement ratio, micro-cement type, admixture system, and time after mixing. The water–cement ratio controlled the general rheological level and stability of the grout, while the admixture type and dosage strongly influenced early-age structuration, setting behavior, and workability retention. Lower water–cement ratios generally improved stability but increased rheological resistance, whereas higher water–cement ratios improved flowability and filtration but increased the risk of water separation in some mixtures.

The study confirmed that injection grout suitability cannot be assessed using a single test parameter. A mixture with good flowability may still be unsuitable if it shows poor stability, excessive water separation, delayed setting, or insufficient filtration performance. Similarly, a stable mix may be unsuitable if its yield stress or plastic viscosity becomes too high for pumping and fracture penetration. Therefore, fresh-state injection grout design should be based on a combined evaluation of rheology, stability, filtration, setting behavior, and quality-control parameters.

The filter pump results demonstrated that penetrability is affected not only by cement fineness but also by the rheological and stability conditions of the injection grout. This confirms that filtration performance should be interpreted as a coupled material response rather than only as a particle-size-related property.

Based on the experimental database, an Excel-based injection grout mix proportioning tool was developed. The tool allows user-defined performance criteria to be compared with measured grout properties and provides recommended grout mixtures based on the selected targets. This demonstrates the feasibility of translating laboratory test results into a practical decision-support system for performance-based grout mix selection.

Overall, the thesis shows that a systematic, data-driven approach can improve the selection and optimization of cement-based injection grouts. The developed experimental database and proportioning tool provide a practical foundation for moving beyond trial-and-error grout design toward a more performance-based methodology for underground injection applications.

7 Recommendations for future works

The present study developed an experimental database and an Excel-based grout mix proportioning tool using key fresh-state properties of cement-based injection grouts. Although the results show that performance-based grout selection is feasible, further work is recommended to improve the reliability and practical applicability of the method.

First, the experimental database should be expanded by including additional micro-cement types, especially UF12, together with wider water–cement ratios and admixture dosages. This would improve the understanding of how cement fineness and chemical admixtures influence rheology, filtration, stability, and setting behavior.

Second, selected injection grout mixtures should be tested with repeated trials to evaluate experimental variability. Rheological measurements, water separation, and filter pump tests can be sensitive to mixing procedure, temperature, testing time, and operator handling. Replicate testing would therefore improve confidence in the measured values and help define more reliable performance windows.

Third, the threshold values used in the proportioning tool should be further refined. Limits for yield stress, plastic viscosity, water separation, filtration volume, setting time, and air content should be connected more clearly to practical grouting requirements such as fracture aperture, pumping distance, injection pressure, and required working time.

Fourth, the developed tool should be validated using field trials or larger-scale laboratory injection tests. This is important because laboratory performance does not always fully represent grout behavior under real injection conditions. Validation would show whether the recommended mixtures provide suitable pumpability, penetrability, stability, and setting behavior in practice.

Finally, future development of the tool could include weighted scoring and improved ranking logic. Different injection grouting applications may require different priorities; for example, fine-fracture injections may need high filtration performance, while rapid sealing may require shorter setting time. Including these application-based priorities would make the tool more flexible and useful for practical grout mix selection.

Overall, future work should focus on expanding the database, improving repeatability, validating the tool under practical conditions, and linking laboratory performance to field requirements. These improvements would strengthen the proposed approach and support the development of a more reliable, data-driven method for injection grout mix design.

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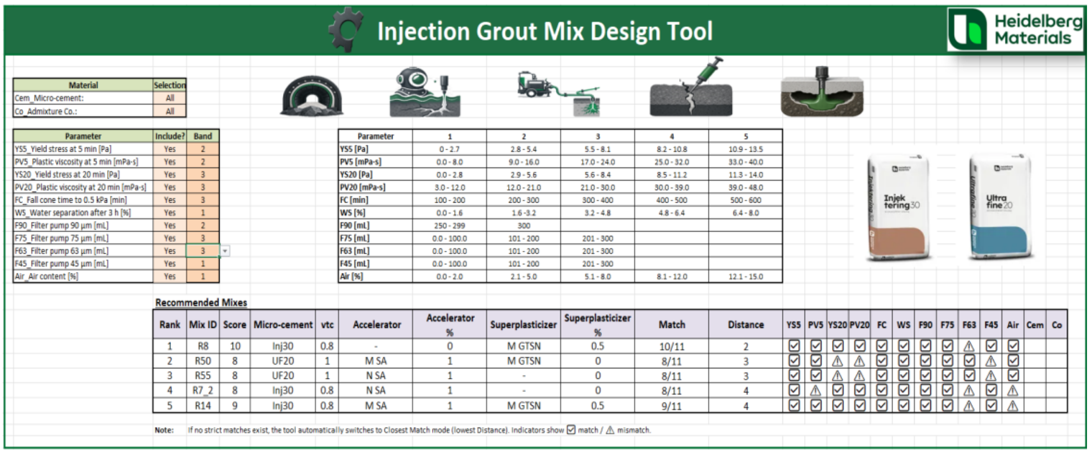
9 Appendix A- Injection Grout Tool



Material	Selection
Cem_Micro-cement:	All
Co_Admixture Co.:	All

Parameter	Include?	Band
YS5_Yield stress at 5 min [Pa]	Yes	2
PV5_Plastic viscosity at 5 min [mPa·s]	Yes	2
YS20_Yield stress at 20 min [Pa]	Yes	3
PV20_Plastic viscosity at 20 min [mPa·s]	Yes	3
FC_Fall cone time to 0.5 kPa [min]	Yes	3
WS_Water separation after 3 h [%]	Yes	1
F90_Filter pump 90 µm [mL]	Yes	2
F75_Filter pump 75 µm [mL]	Yes	3
F63_Filter pump 63 µm [mL]	Yes	3
F45_Filter pump 45 µm [mL]	Yes	1
Air_Air content [%]	Yes	1

Parameter	1	2	3	4	5
YS5 [Pa]	0 - 2.7	2.8 - 5.4	5.5 - 8.1	8.2 - 10.8	10.9 - 13.5
PV5 [mPa·s]	0.0 - 8.0	9.0 - 16.0	17.0 - 24.0	25.0 - 32.0	33.0 - 40.0
YS20 [Pa]	0.0 - 2.8	2.9 - 5.6	5.6 - 8.4	8.5 - 11.2	11.3 - 14.0
PV20 [mPa·s]	3.0 - 12.0	12.0 - 21.0	21.0 - 30.0	30.0 - 39.0	39.0 - 48.0
FC [min]	100 - 200	200 - 300	300 - 400	400 - 500	500 - 600
WS [%]	0.0 - 1.6	1.6 -3.2	3.2 - 4.8	4.8 - 6.4	6.4 - 8.0
F90 [mL]	250 - 299	300			
F75 [mL]	0.0 - 100.0	101 - 200	201 - 300		
F63 [mL]	0.0 - 100.0	101 - 200	201 - 300		
F45 [mL]	0.0 - 100.0	101 - 200	201 - 300		
Air [%]	0.0 - 2.0	2.1 - 5.0	5.1 - 8.0	8.1 - 12.0	12.1 - 15.0

Recommended Mixes

Rank	Mix ID	Score	Micro-cement	vtc	Accelerator	Accelerator %	Superplasticizer	Superplasticizer %	Match	Distance	YS5	PV5	YS20	PV20	FC	WS	F90	F75	F63	F45	Air	Cem	Co
1	R8	10	Inj30	0.8	-	0	M GTSN	0.5	10/11	2	☑	☑	☑	☑	☑	☑	☑	☑	⚠	☑	☑		
2	R50	8	UF20	1	M SA	1	M GTSN	0	8/11	3	☑	☑	⚠	⚠	☑	☑	☑	☑	☑	⚠	☑		
3	R55	8	UF20	1	N SA	1	-	0	8/11	3	☑	☑	⚠	⚠	☑	☑	☑	☑	☑	⚠	☑		
4	R7_2	8	Inj30	0.8	N SA	1	-	0	8/11	4	☑	⚠	☑	☑	☑	☑	☑	☑	⚠	☑	⚠		
5	R14	9	Inj30	0.8	M SA	1	M GTSN	0.5	9/11	4	☑	☑	☑	☑	☑	☑	☑	☑	⚠	☑	⚠		

Note: If no strict matches exist, the tool automatically switches to Closest Match mode (lowest Distance). Indicators show ☑ match / ⚠ mismatch.

10 Appendix B – Injection Grout Recipes

Recipe No.	Cement Type	w/c Ratio	Accelerator	Accel Dosage (%)	Flow Agent	Flow Dosage (%)	Group
R1	INJ30	0.8	None	-	None	-	Reference
R2	INJ30	0.8	M SA	1	None	-	Only Accelerator
R3	INJ30	0.8	M SA	2	None	-	Only Accelerator
R4	INJ30	0.8	iAcc1	1	None	-	Only Accelerator
R5	INJ30	0.8	iAcc1	2	None	-	Only Accelerator
R6	INJ30	0.8	N SA	2	None	-	Only Accelerator
R7	INJ30	0.8	N SA	4	None	-	Only Accelerator
R7_2	INJ30	0.8	N SA	1	None	-	Only Accelerator
R8	INJ30	0.8	None	-	M GTSN	0.5	Only Flow Agent
R9	INJ30	0.8	None	-	M GTSN	1.5	Only Flow Agent
R9_2	INJ30	0.8	None	-	M GTSN	1	Only Flow Agent
R10	INJ30	0.8	None	-	iFlow1	0.3	Only Flow Agent
R11	INJ30	0.8	None	-	iFlow1	0.5	Only Flow Agent
R12	INJ30	0.8	None	-	N SP-1	0.5	Only Flow Agent
R13	INJ30	0.8	None	-	N SP-1	1	Only Flow Agent
R14	INJ30	0.8	M SA	1	M GTSN	0.5	Combo
R15	INJ30	0.8	M SA	1	M GTSN	1.5	Combo
R15_2	INJ30	0.8	M SA	1	M GTSN	1	Combo
R16	INJ30	0.8	M SA	2	M GTSN	0.5	Combo
R17	INJ30	0.8	M SA	2	M GTSN	1.5	Combo
R17_2	INJ30	0.8	M SA	2	M GTSN	1	Combo
R18	INJ30	0.8	iAcc1	1	iFlow1	0.3	Combo
R19	INJ30	0.8	iAcc1	1	iFlow1	0.5	Combo
R20	INJ30	0.8	iAcc1	2	iFlow1	0.3	Combo
R21	INJ30	0.8	iAcc1	2	iFlow1	0.5	Combo

R22	INJ30	0.8	N SA	2	N SP-1	0.5	Combo
R23	INJ30	0.8	N SA	2	N SP-1	1	Combo
R24	INJ30	0.8	N SA	4	N SP-1	0.5	Combo
R24_2	INJ30	0.8	N SA	1	N SP-1	0.5	Combo
R25	INJ30	0.8	N SA	4	N SP-1	1	Combo
R25_2	INJ30	0.8	N SA	1	N SP-1	1	Combo
R26	INJ30	1	None	-	None	-	Reference
R27	INJ30	1	M SA	1	None	-	Only Accelerator
R28	INJ30	1	M SA	2	None	-	Only Accelerator
R29	INJ30	1	iAcc1	1	None	-	Only Accelerator
R30	INJ30	1	iAcc1	2	None	-	Only Accelerator
R31	INJ30	1	N SA	2	None	-	Only Accelerator
R32	INJ30	1	N SA	4	None	-	Only Accelerator
R32_2	INJ30	1	N SA	1	None	-	Only Accelerator
R33	INJ30	1	None	-	M GTSN	0.5	Only Flow Agent
R34	INJ30	1	None	-	M GTSN	1.5	Only Flow Agent
R34_2	INJ30	1	None	-	M GTSN	1	Only Flow Agent
R35	INJ30	1	None	-	iFlow1	0.3	Only Flow Agent
R36	INJ30	1	None	-	iFlow1	0.5	Only Flow Agent
R37	INJ30	1	M SA	1	M GTSN	0.5	Combo
R38	INJ30	1	M SA	1	M GTSN	1	Combo
R39	INJ30	1	M SA	2	M GTSN	0.5	Combo
R40	INJ30	1	M SA	2	M GTSN	1	Combo
R41	INJ30	1	iAcc1	1	iFlow1	0.3	Combo
R42	INJ30	1	iAcc1	1	iFlow1	0.5	Combo
R43	INJ30	1	iAcc1	2	iFlow1	0.3	Combo
R44	INJ30	1	iAcc1	2	iFlow1	0.5	Combo
R45	INJ30	1	N SA	2	N SP-1	0.5	Combo
R46	INJ30	1	N SA	2	N SP-1	1	Combo

R47	INJ30	1	N SA	1	N SP-1	0.5	Combo
R48	INJ30	1	N SA	1	N SP-1	1	Combo
R49	UF20	1	None	-	None	-	Reference
R50	UF20	1	M SA	1	None	-	Only Accelerator
R51	UF20	1	M SA	2	None	-	Only Accelerator
R52	UF20	1	iAcc1	1	None	-	Only Accelerator
R53	UF20	1	iAcc1	2	None	-	Only Accelerator
R54	UF20	1	N SA	2	None	-	Only Accelerator
R55	UF20	1	N SA	1	None	-	Only Accelerator
R56	UF20	1	None	-	M GTSN	0.5	Only Flow Agent
R57	UF20	1	None	-	M GTSN	1	Only Flow Agent
R58	UF20	1	None	-	iFlow1	0.3	Only Flow Agent
R59	UF20	1	None	-	iFlow1	0.5	Only Flow Agent
R60	UF20	1	M SA	1	M GTSN	0.5	Combo
R61	UF20	1	M SA	1	M GTSN	1	Combo
R62	UF20	1	M SA	2	M GTSN	0.5	Combo
R63	UF20	1	M SA	2	M GTSN	1	Combo
R64	UF20	1	iAcc1	1	iFlow1	0.3	Combo
R65	UF20	1	iAcc1	1	iFlow1	0.5	Combo
R66	UF20	1	iAcc1	2	iFlow1	0.3	Combo
R67	UF20	1	iAcc1	2	iFlow1	0.5	Combo
R68	UF20	1	N SA	2	N SP-1	0.5	Combo
R69	UF20	1	N SA	2	N SP-1	1	Combo
R70	UF20	1	N SA	1	N SP-1	0.5	Combo
R71	UF20	1	N SA	1	N SP-1	1	Combo
R72	UF20	1.2	None	-	None	-	Reference
R73	UF20	1.2	M SA	1	None	-	Only Accelerator
R74	UF20	1.2	M SA	2	None	-	Only Accelerator
R75	UF20	1.2	iAcc1	1	None	-	Only Accelerator

R76	UF20	1.2	iAcc1	2	None	-	Only Accelerator
R77	UF20	1.2	N SA	2	None	-	Only Accelerator
R78	UF20	1.2	N SA	1	None	-	Only Accelerator
R79	UF20	1.2	None	-	M GTSN	0.5	Only Flow Agent
R80	UF20	1.2	None	-	M GTSN	1	Only Flow Agent
R81	UF20	1.2	None	-	iFlow1	0.3	Only Flow Agent
R82	UF20	1.2	None	-	iFlow1	0.5	Only Flow Agent
R83	UF20	1.2	M SA	1	M GTSN	0.5	Combo
R84	UF20	1.2	M SA	1	M GTSN	1	Combo
R85	UF20	1.2	M SA	2	M GTSN	0.5	Combo
R86	UF20	1.2	M SA	2	M GTSN	1	Combo
R87	UF20	1.2	iAcc1	1	iFlow1	0.3	Combo
R88	UF20	1.2	iAcc1	1	iFlow1	0.5	Combo
R89	UF20	1.2	iAcc1	2	iFlow1	0.3	Combo
R90	UF20	1.2	iAcc1	2	iFlow1	0.5	Combo
R91	UF20	1.2	N SA	2	N SP-1	0.5	Combo
R92	UF20	1.2	N SA	2	N SP-1	1	Combo
R93	UF20	1.2	N SA	1	N SP-1	0.5	Combo