



Development of a Design Model for Selecting Optimal Parameters for Permeation Grouting Based on Soil Permeability Coefficient and Grout Rheological Behavior

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Abstract

This study aimed to determine the optimal parameters of cement grout for permeation grouting and to develop a practical design model for selecting the water-to-cement ratio, injection pressure, and grout permeability coefficient according to soil permeability and grout rheological behavior. An experimental laboratory study was conducted using reconstituted sandy soils with different gradations and fines contents and cement grouts prepared at water-to-cement ratios of 0.6, 0.8, 1.00, 1.20, and 1.50. Grain-size distribution, soil permeability, grout rheology, stability, and permeation-grouting behavior were evaluated. Soil permeability tests were performed according to ASTM D2434-87, while rheological testing measured shear stress, shear rate, apparent viscosity, and yield stress. A specially designed laboratory grouting chamber was constructed to simulate grout injection through porous media under different pressures and to determine the grout permeability coefficient (KG). Data were analyzed using regression, curve fitting, correlation analysis, comparison with classical permeability relationships, and assessment of Darcy's law. Cement grout exhibited Bingham non-Newtonian behavior across all tested mixtures. The fitted rheological equations showed high coefficients of determination, including $R^2 = 0.9812$, 0.9949 , and 0.9881 for W/C ratios of 0.6, 0.8, and 1.00, respectively. Increasing the water-to-cement ratio reduced yield stress and plastic viscosity and improved penetrability. The hydraulic-gradient-flow-velocity relationship was linear at low pressure ($i = 287.85v$, $R^2 = 0.8467$) but became nonlinear at high pressure ($i = 1773.9v^{1.5152}$, $R^2 = 0.9944$), indicating deviation from Darcy behavior. KG increased with the water-to-cement ratio and was strongly governed by grout viscosity. Increasing injection pressure enhanced flow only up to a threshold, after which viscosity became the dominant controlling factor. The results demonstrate that successful permeation grouting depends on the coupled effects of soil permeability, grout rheology, water-to-cement ratio, and injection pressure; accordingly, the proposed design model provides a practical framework for selecting appropriate grouting parameters and evaluating groutability in sandy soils.

Keywords: Permeation grouting; cement grout; soil permeability coefficient; grout rheology; grout permeability coefficient; injection pressure; water-to-cement ratio; design model.

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1. Introduction

Ground improvement has become an indispensable component of contemporary geotechnical engineering because increasingly complex infrastructure projects are being constructed in deposits characterized by inadequate strength, excessive permeability, high compressibility, or heterogeneous pore structures. Among the available

improvement techniques, grouting has attracted particular attention because it can modify the mechanical and hydraulic properties of soils with relatively limited disturbance to the original ground structure. Grouting methods are now used in foundations, tunnels, underground structures, dams, shafts, excavations, pipe-jacking works, and other projects in which seepage control, reinforcement, void filling, or reduction of



deformation is required. A broad review of ground-grouting technologies has emphasized that their effectiveness depends on the coordinated selection of grout composition, soil condition, injection method, and operational parameters rather than on any single variable considered independently [1]. Applications in underground engineering similarly demonstrate that grouting can perform both structural and hydraulic functions, including reinforcement of weak formations, control of groundwater, filling of fissures and voids, and improvement of construction safety [2]. Recent studies have consequently moved beyond empirical selection of injection parameters toward more quantitative descriptions of grout diffusion, rheology, porous-medium interaction, and the evolution of grout properties during injection. This trend is also reflected in foundation-improvement research, where numerical simulations are increasingly used to understand overburden response, slurry migration, and the interaction between injection processes and soil structure [3]. Despite these advances, predicting the actual penetrability of cementitious grout in granular soil remains difficult because grout flow is governed simultaneously by the pore geometry of the soil, the rheological characteristics of the suspension, the applied pressure, and the time-dependent changes that occur during mixing and injection.

Permeation grouting is particularly sensitive to this interaction because the grout is expected to penetrate the existing void network without causing substantial displacement or fracturing of the soil skeleton. The success of this process therefore depends fundamentally on the relationship between grout-particle dimensions, soil-pore characteristics, hydraulic conductivity, and slurry viscosity. Experimental studies of infiltration grouting in coarse and heterogeneous deposits have shown that injectability cannot be inferred from grain-size criteria alone and that the flow properties of the grout must be considered together with the pore structure of the medium [4]. Similarly, theoretical investigations have demonstrated that the diffusion radius of cement-based grout is directly affected by pore characteristics and by the hydraulic resistance generated within the interconnected voids of the soil [5]. Research on Bingham-fluid infiltration in porous media with different particle-size distributions has further shown that gradation strongly influences grout propagation because changes in pore dimensions and connectivity alter the pressure required to initiate and sustain slurry movement [6]. The significance of tortuosity has also become increasingly evident. A column-hemispherical penetration model for Newtonian

fluids demonstrated that the actual flow path through porous media is longer and more complex than a simplified straight-line representation, thereby affecting diffusion pressure and propagation distance [7]. More recent modeling of spherical infiltration by Bingham slurry has explicitly incorporated porous-medium tortuosity and confirmed that the geometrical complexity of the pore network can materially influence the predicted penetration behavior [8]. These findings collectively indicate that soil permeability should not be viewed merely as a background property but as a central design variable governing whether a selected grout can migrate through a specific granular matrix.

The rheological behavior of cement-based grout is equally important because cement suspensions generally do not behave as simple Newtonian fluids. Their flow is commonly characterized by a finite yield stress and a viscosity that varies with mixture composition and, in some cases, with time and shear history. This behavior has direct implications for injection because a minimum stress must be exceeded before grout movement begins, and thereafter the resistance to flow determines the pressure gradient required to maintain penetration. Experimental investigation of cement-bentonite slurry has confirmed that rheological parameters are closely associated with permeation-grouting reinforcement performance and that changes in mixture composition alter both injectability and the resulting improvement effect [9]. The time dependence of grout behavior is also important. Measurements obtained during shield-tunnel grouting have shown that grout parameters can evolve substantially after mixing, meaning that a mixture characterized at one time may not exhibit identical flow behavior later in the injection process [10]. Research comparing time-dependent viscosity slurry with cement-clay slurry for anti-seepage applications likewise demonstrated that viscosity evolution has a significant effect on diffusion and sealing performance [11]. A displacement-diffusion model developed for time-varying slurry in unsaturated media has further shown that incorporating changing rheological parameters produces a more realistic representation of slurry migration than assuming constant fluid properties [12]. These studies highlight the necessity of characterizing grout rheology under controlled conditions before attempting to relate injection pressure to penetrability. They also suggest that water-to-cement ratio, which directly affects particle concentration and internal resistance, is likely to be one of the most consequential variables in cement-grout design.

The water-to-cement ratio affects not only viscosity and yield stress but also stability, segregation potential, flowability, and the ability of grout to enter small pore spaces. A relatively low water content generally produces a denser grout with higher internal resistance and better suspension stability, whereas a higher water content improves mobility but may increase bleeding or particle settlement. This balance between stability and injectability is a recurrent issue in grout-material design. Studies of fresh and hardened grout properties for structural applications have demonstrated that mixture proportions control flow characteristics at the fresh stage and influence subsequent hardened performance [13]. Research on optimized synchronous grouting mixtures for shield tunnels has similarly shown that mix proportions must be selected to satisfy multiple, and sometimes competing, requirements relating to flow, stability, setting, and engineering performance [14]. The use of alternative or modified slurry systems reinforces this point. Modified sodium bentonite has been studied specifically in relation to its diffusion and plugging mechanisms, showing how changes in material structure can affect both transport and sealing behavior [15]. Sodium silicate grouting has also been reviewed from the perspectives of transport mechanisms, environmental effects, and future research needs, illustrating the broader importance of understanding how grout chemistry and pore-scale interactions determine performance in porous media [16]. Even emerging recycled slurry materials, such as waste silty clay proposed for slurry-shield applications, are being evaluated in terms of whether their material properties can provide acceptable flow and engineering performance [17]. Thus, although numerous grout formulations are available, a design methodology for conventional cement grout remains valuable because Portland-cement systems continue to be widely used and their performance depends strongly on appropriately balancing rheology and soil compatibility.

Injection pressure represents another central parameter, but its effect cannot be interpreted independently of grout viscosity and soil permeability. In practical terms, increasing pressure can increase grout discharge and diffusion distance, but excessively high pressure may alter the intended injection mechanism by causing local disturbance, uplift, fracturing, or preferential flow. High-pressure cyclic grouting has been investigated in soft soils as a means of improving grout distribution and reinforcement, demonstrating the importance of controlling the temporal and mechanical characteristics of the injection process [18]. Research on high-pressure jet-disturbance grouting has also

shown that diffusion parameters are strongly influenced by the pressure regime and by disturbance of the surrounding medium [19]. These mechanisms differ from true permeation, yet they illustrate why pressure cannot simply be increased without considering the soil response. In permeation grouting, the objective is to achieve penetration through existing pore channels rather than to create new fractures or substantially rearrange particles. Studies of seepage failure in silty fine sand are therefore relevant because they demonstrate the susceptibility of granular soils to hydraulic instability when gradients become sufficiently large [20]. A rational permeation-grouting design must consequently identify a pressure range high enough to overcome grout yield resistance and hydraulic losses, but low enough to preserve the intended pore-scale infiltration mechanism.

The relationship between hydraulic gradient and grout-flow velocity is also more complex than that governing ordinary water seepage. Classical Darcy flow assumes a proportional relationship between gradient and velocity for a Newtonian fluid under laminar conditions, whereas cement grout possesses yield stress, concentration-dependent viscosity, and potential filtration or particle-retention effects. Studies of foundation grouting in goaf areas have incorporated actual diffusion paths to improve representation of seepage-grouting mechanisms and have shown that geometric assumptions can significantly affect predicted pressure and propagation characteristics [21]. Subsequent work on viscous time-varying fluids similarly emphasized the importance of diffusion-path effects when describing permeation behavior [22]. A modified spherical and cylindrical permeation-diffusion model that incorporates deep-bed filtration has further demonstrated that particle retention within porous media can progressively alter slurry transport and effective permeability during grouting [23]. Columnar penetration models for time-varying Newtonian fluids have also been experimentally and theoretically investigated to verify how grout diffusion changes with fluid characteristics and geometry [24]. Together, these studies suggest that direct application of simplified hydraulic equations to cement-grout flow may produce substantial error unless the constitutive behavior of the grout and the actual pore-scale transport mechanisms are considered explicitly. For this reason, determining an experimentally based grout permeability coefficient may provide a useful bridge between the measurable hydraulic properties of the soil and the flow characteristics of the grout.

The importance of quantitatively linking soil permeability and grouting parameters has already been recognized in several engineering contexts. A quantitative design method developed for grouting in sand layers in the Qingdao Metro demonstrated the practical value of integrating formation characteristics and grouting parameters into a systematic design procedure rather than relying solely on experience-based selection [25]. Investigations of slurry diffusion at the pile tips of bored piles in gravel-pebble strata have likewise shown that diffusion behavior depends on both the properties of the granular formation and the selected injection conditions [26]. Studies involving vacuum-assisted penetration of waterborne polyurethane cementitious composite slurry have expanded the range of approaches used to enhance infiltration and have further highlighted the importance of controlling the driving mechanism for slurry transport [27]. Research into lubricating slurries for pipe-jacking applications has also demonstrated that fluid behavior and circulation characteristics can substantially influence interface performance and transport under field conditions [28]. In saline strata, the impermeability of filter cakes formed by lubricating slurry has been examined as another manifestation of the interaction between slurry properties and porous ground conditions [29]. Although these applications differ in purpose and material system, they converge on a common principle: engineering performance depends on matching the transport characteristics of the injected or circulated material to the hydraulic and structural characteristics of the surrounding ground.

Recent research has also emphasized the need to improve the predictive capability of grouting models by integrating experimental data, constitutive behavior, and more realistic representations of the subsurface. Numerical reviews of overburden grouting indicate that model reliability is strongly influenced by how accurately slurry properties, soil or rock heterogeneity, and injection conditions are represented [3]. Experimental and theoretical work increasingly incorporates nonlinear flow, time-dependent rheology, tortuosity, and filtration, reflecting recognition that overly simplified assumptions may be inadequate for design. At the same time, alternative binders and more sustainable grout materials are being developed. An optimized fly ash-slag geopolymers has recently been investigated for reinforcement of soil-rock mixtures, demonstrating that effective grouting can potentially be achieved with materials having different rheological and mechanical characteristics from conventional cement

systems [30]. Such developments make mechanistic understanding even more important, because design procedures must ultimately be capable of accommodating different slurry rheologies rather than being restricted to a single empirical mixture. Nevertheless, conventional cement grout remains a primary reference material for permeation grouting, and its relatively well-established composition makes it especially suitable for clarifying fundamental relationships among rheological properties, permeability, and injection behavior.

A further challenge concerns the spatial and temporal variability of grout diffusion in heterogeneous media. Research on pile-tip grouting, shield grouting, soft-soil injection, and granular-media infiltration has consistently shown that grout does not propagate as a perfectly uniform front. Local pore-size variations, changes in hydraulic resistance, preferential pathways, filtration, and rheological evolution can all modify the geometry of diffusion [26]. Experimental studies of reinforcement using cement-bentonite slurry have similarly demonstrated that the final grouted zone is controlled by a combination of slurry rheology and the surrounding porous structure [9]. Investigations of infiltration in moraine deposits have shown that heterogeneous particle distributions can lead to substantial differences in injectability even where average grain-size characteristics appear comparable [4]. Moreover, the diffusion and plugging behavior of modified bentonite systems confirms that progressive deposition or retention of particles may change the effective pore network during injection itself [15]. These observations reinforce the need for laboratory systems capable of simultaneously measuring soil permeability, grout-flow response, pressure, and effective grout permeability under controlled conditions. Such experiments can provide parameters suitable for practical design while also serving as a basis for calibrating more sophisticated analytical or numerical models.

Despite the growing body of work on grout diffusion, rheology, material modification, and injection mechanics, an important practical gap remains in establishing a direct and experimentally supported framework that links the permeability of granular soil to the rheological behavior of conventional cement grout and then uses that relationship to select suitable injection parameters. Existing studies have often concentrated on specific aspects of the problem, such as diffusion geometry [24], tortuosity [8], time-dependent viscosity [12], deep-bed filtration [23], high-pressure disturbance [19], or specialized slurry formulations [27]. Other investigations have focused on particular applications,

including metro sand layers [25], pile-tip reinforcement [26], pipe-jacking lubrication [28], shield tunneling [14], or foundation treatment in mined-out areas [21]. While these contributions have substantially improved understanding of grouting phenomena, field practice still requires a relatively simple method by which readily measurable soil parameters can be combined with grout rheological characteristics to determine whether permeation is feasible and, if so, what water-to-cement ratio and pressure range should be selected. This need is especially important for sandy soils containing variable fines, because increasing fines content can sharply reduce permeability and alter the validity of classical hydraulic relationships. A laboratory-based design approach that integrates soil permeability, grout rheology, grout permeability coefficient, and injection-pressure response could therefore reduce dependence on trial-and-error procedures and provide a more defensible basis for parameter selection.

Accordingly, the aim of this study was to experimentally investigate the coupled effects of soil permeability, cement-grout rheological behavior, water-to-cement ratio, and injection pressure on permeation grouting and to develop a practical design model for selecting the optimum grout parameters and evaluating groutability in sandy soils.

2. Methodology

2.1. *Materials, Sample Preparation, and Characterization*

The experimental program was designed to investigate, within a unified laboratory framework, the physical and hydraulic characteristics of sandy soils, the rheological behavior of cement grout, and the interaction between grout

properties and soil permeability during permeation grouting. The laboratory conditions were selected so that the principal mechanisms governing field grouting could be reproduced as closely as practicable under controlled conditions. Ordinary Portland cement was used as the cementitious material because of its widespread application in permeation-grouting projects, ready availability, and suitability for comparison with conventional cement-grout systems. The physical and chemical properties of the cement were checked in accordance with the relevant standards before grout preparation. Potable water was used for all grout mixtures to minimize the possibility of undesirable changes in cement hydration or grout rheological behavior resulting from dissolved impurities. The porous medium consisted of reconstituted sandy soils prepared with different particle-size distributions and fines contents in order to provide a range of hydraulic and groutability conditions. The selection of the investigated gradations was guided by the groutability ranges proposed by Houlsby and Littlejohn for cement-based grouts, and the reconstructed specimens were subsequently tested for both water permeability and cement-grout penetrability. For each soil mixture, the characteristic particle sizes D₁₀, D₁₅, D₃₀, D₅₀, and D₆₀ were determined from the grain-size distribution curve, together with the coefficient of uniformity, coefficient of curvature, groutability indices, fines-related characteristics, and soil classification according to the Unified Soil Classification System. Figure 1 presents the particle-size distribution curves of the reconstructed fine- and coarse-sand mixtures, while Table 1 summarizes the principal gradation parameters and preliminary groutability classifications of the 20 soil samples.

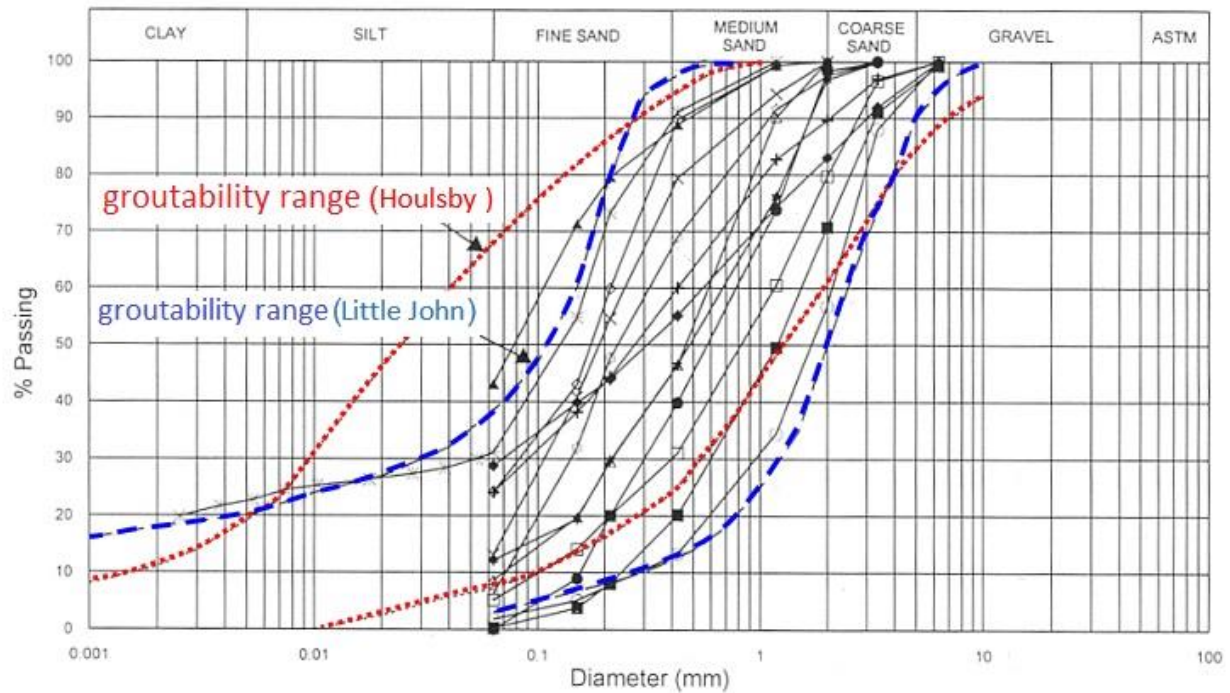


Figure 1. Distribution and grain-size distribution curves of the reconstituted sand samples (fine and coarse sand).

Table 1. Particle sizes and groutability ratio

Sample	USCS	D10 (mm)	D15 (mm)	D30 (mm)	D60 (mm)	Cu	Cc	Nc	N	Groutability
1	SW	1.42	2.12	2.65	3.60	2.5	1.4	15.8	35.3	P
2	SW	1.35	2.12	2.42	3.60	2.7	1.2	15.0	35.3	P
3	SW-SM	0.42	1.74	1.98	2.85	6.8	3.3	4.7	29.0	I
4	SW-SC	1.05	1.83	1.83	2.30	2.2	1.4	11.7	30.5	P
5	SP	0.153	1.62	2.02	2.60	17.0	10.3	1.7	27.0	C
6	SP	1.22	1.62	1.78	2.40	2.0	1.1	13.6	27.0	P
7	SP-SW	0.25	1.38	1.85	2.45	9.8	5.6	2.8	23.0	I
8	SP-SW	1.05	1.38	1.55	1.98	1.9	1.2	11.7	23.0	C
9	SW	0.268	1.96	1.96	2.13	7.9	6.7	3.0	32.7	C
10	SP-SC	0.32	1.45	1.50	1.80	5.6	3.9	3.6	24.2	I
11	SP-SC	1.20	1.34	1.50	2.32	1.9	0.8	13.3	22.3	C
12	SM	0.055	0.09	0.45	1.32	24.0	2.8	0.6	1.5	I
13	SW	0.238	0.317	1.02	1.54	6.5	2.8	2.6	5.3	I
14	SM	2.13	2.188	2.45	3.60	1.7	0.8	23.7	36.5	P
15	SM	0.98	2.202	2.45	3.60	3.7	1.7	10.9	36.7	C
16	SM	1.32	1.50	1.85	2.85	2.2	0.9	14.7	25.0	C
17	SM	2.131	2.202	2.65	3.60	1.7	0.9	23.7	36.7	P
18	SC	0.32	0.55	1.12	1.62	5.1	2.4	3.6	9.2	I
19	SC	0.26	0.55	0.86	1.62	6.2	1.8	2.9	9.2	I
20	SC	0.64	1.96	2.05	2.45	3.8	2.7	7.1	32.7	C

Note. $Cu = D_{60}/D_{10}$; $Cc = (D_{30})^2/(D_{60} \times D_{10})$; $Nc = D_{10}/d_{95}$, where $d_{95} = 0.09$ mm; $N = D_{15}/d_{85}$, where $d_{85} = 0.06$ mm. Groutability classifications were defined as P = possible, C = conditional or requiring special conditions, and I = impossible.

Cement grouts were prepared at five water-to-cement ratios, namely 0.6, 0.8, 1.00, 1.20, and 1.50, to encompass mixtures ranging from relatively dense and viscous suspensions to more fluid grouts with greater potential penetrability. For each mixture, predetermined quantities of

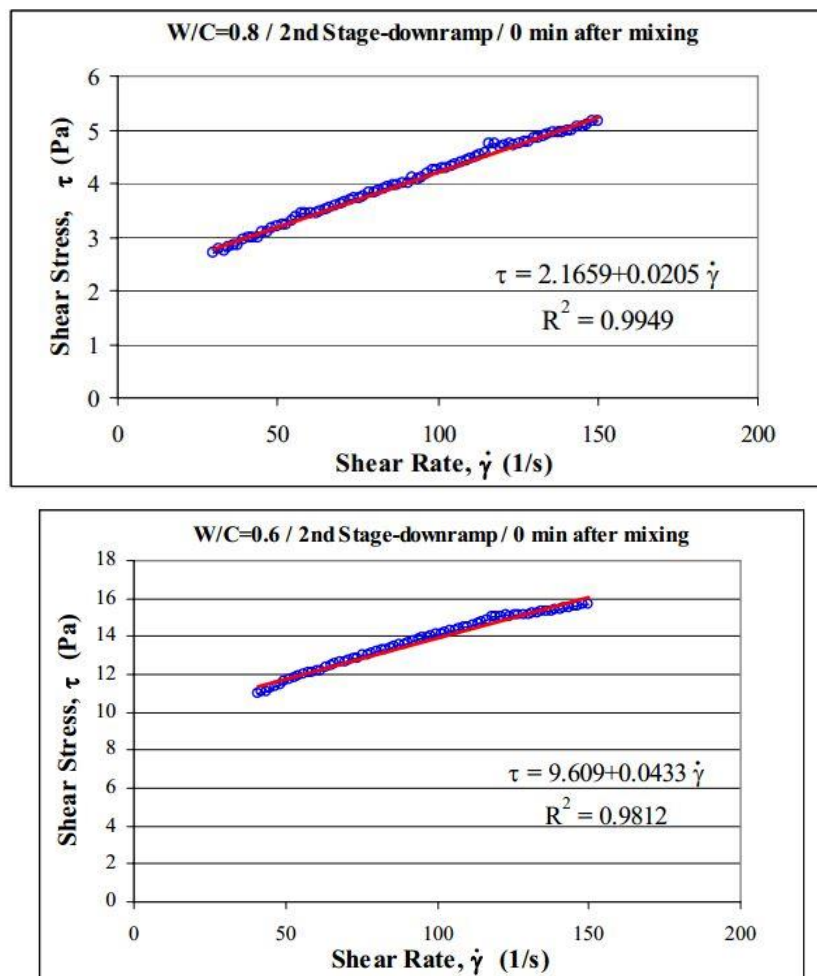
cement and water were mechanically mixed at a controlled volume. Preliminary trials indicated that mixing duration had a marked effect on grout homogeneity and on the repeatability of rheological measurements; consequently, a constant mixing procedure was adopted for all subsequent

experiments. Rheological characterization was performed using a rotary viscometer equipped with a coaxial-cylinder arrangement, as illustrated in Figure 2. During testing, shear stress and shear rate were recorded over the prescribed range, and the corresponding apparent viscosity and yield stress were determined. The resulting flow curves were used to characterize the constitutive behavior of the cement grout. The experimental response indicated that the grout behaved

as a non-Newtonian Bingham material, for which the shear stress can be represented by the general relation $\tau = \tau_0 + \mu_p \dot{\gamma}$, where τ denotes shear stress, τ_0 is the yield stress, μ_p is the plastic viscosity, and $\dot{\gamma}$ is the shear rate. The rheological response obtained for the five water-to-cement ratios is presented in Figure 3 and provided the basis for subsequently relating grout viscosity and yield resistance to flow through the soil pore network.



Figure 2. Rotary viscometer (rheometer) with a coaxial cylinder.



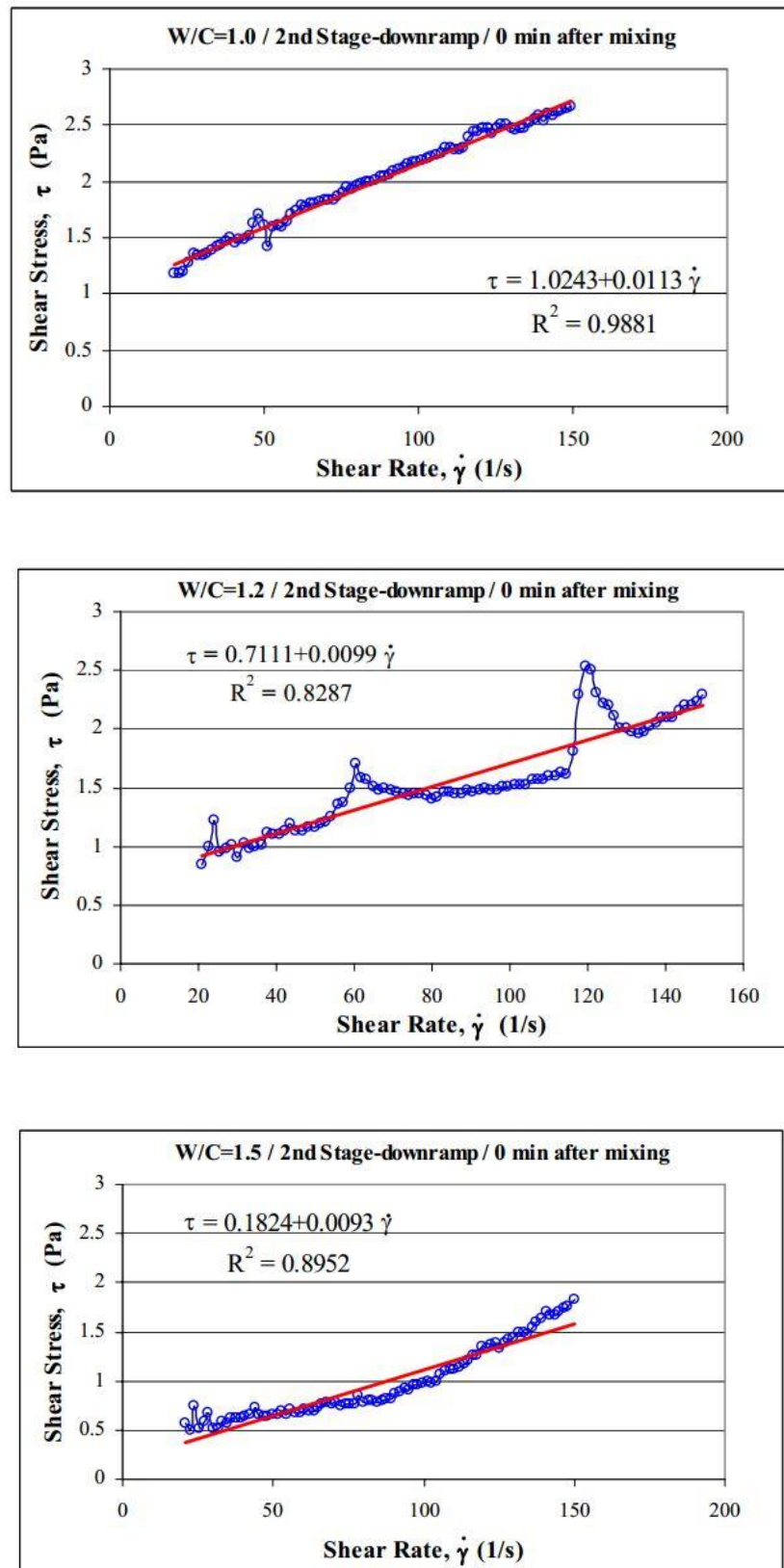


Figure 3. Bingham model of cement grout at W/C ratios of 0.6, 0.8, 1.00, 1.20, and 1.50.

2.2. Permeability and Permeation-Grouting Experimental Program

The hydraulic behavior of the reconstructed soils was evaluated before grout injection in order to establish the permeability characteristics of the porous media under controlled laboratory conditions. Soil permeability tests were conducted in accordance with ASTM D2434-87, and the coefficient of permeability was determined for the different gradations. Particular attention was given to the effects of particle-size distribution, D₁₀, fines content, void ratio, and applied consolidation pressure because these variables directly influence the dimensions, continuity, and connectivity of the pore channels through which grout must propagate. The measurements obtained from these tests were subsequently used as the hydraulic reference for the grout-injection experiments and for comparison with classical permeability relationships. In the preliminary grouting trials, the use of small test chambers and narrow flow tubes led to frequent blockage of cement grout within the soil specimens.

Under such conditions, sustained grout movement could be achieved only by increasing the water-to-cement ratio or by imposing relatively high injection pressures, the latter introducing the possibility of soil disturbance or hydraulic fracturing rather than true permeation. To overcome these limitations, a dedicated laboratory grouting chamber was designed and constructed specifically for this study. The chamber was configured to permit controlled placement of the soil specimen, application of different effective injection pressures, propagation of grout through the porous medium, and continuous observation or measurement of discharge and associated flow behavior. The apparatus also permitted the simultaneous evaluation of soil and grout parameters and enabled the grout permeability coefficient to be derived under different combinations of soil condition, grout composition, and injection pressure. A general view and schematic representation of the experimental chamber are provided in Figure 4.



Figure 4. General view of the designed permeation-grouting chamber and experimental configuration.

The permeation-grouting experiments were performed systematically for the selected soil and grout combinations. For each test, the prepared soil specimen was placed in the grouting chamber under the prescribed condition, after which a fresh cement grout corresponding to the selected water-to-cement ratio was introduced into the system. The required injection pressure was then applied and maintained according to the experimental program, while grout flow rate, pressure variation, elapsed injection time, and penetrability behavior were monitored and recorded. A range of injection pressures was investigated so that the

relative influence of pressure and grout rheology could be distinguished and the transition from pressure-controlled to viscosity-controlled flow could be evaluated. The principal experimental outcomes were the groutability of each soil-grout combination, the effect of the water-to-cement ratio on penetrability, the influence of injection pressure on grout flow, and the determination of the grout permeability coefficient, denoted as K_G . The coefficient K_G was calculated under the different experimental conditions using the measured injection pressure, discharge rate, specimen dimensions, and hydraulic gradient. These values served as

a quantitative representation of grout movement through the soil and subsequently formed the basis for developing the proposed design relationships and parameter-selection charts.

2.3. Data Analysis and Development of the Design Model

The experimental data were analyzed using a combination of regression analysis, curve-fitting procedures, correlation analysis, and comparative evaluation against conventional soil-permeability formulations. Rheological data were fitted to the Bingham constitutive model to quantify the yield stress and plastic viscosity associated with each water-to-cement ratio, whereas soil-permeability data were examined in relation to gradation parameters, void ratio, fines content, and characteristic particle size. The grout-flow results were evaluated by relating hydraulic gradient to flow velocity and by examining whether the observed response was consistent with Darcy-type linear behavior or exhibited nonlinear characteristics under the tested injection conditions. Relationships between injection pressure, grout flow rate, water-to-cement ratio, and K_G were subsequently established through regression and curve fitting. The measured soil permeability and grout permeability coefficients were then integrated with the rheological parameters to develop practical design relationships for selecting an appropriate water-to-cement ratio and injection pressure and for estimating the likelihood of successful permeation. The resulting analytical framework was intended to provide a direct connection between measurable soil characteristics and grout-flow properties rather than relying exclusively on empirical groutability criteria. Accordingly, the final design model was developed from the combined results of the soil permeability tests, rheological measurements, and chamber-based permeation-grouting experiments, with the principal design outputs consisting of the recommended grout composition, appropriate injection-pressure range, estimated

K_G , and an assessment of whether successful grout penetration could be achieved under the specified soil conditions.

3. Findings and Results

3.1. Rheological Behavior, Mixing Uniformity, and Grout Stability

The experimental results demonstrated that all cement-grout mixtures exhibited non-Newtonian flow behavior and were satisfactorily represented by the Bingham rheological model. Accordingly, grout flow commenced only after the applied shear stress exceeded a finite yield-stress threshold, after which shear stress increased approximately linearly with shear rate. A systematic dependence of rheological behavior on the water-to-cement ratio was observed. At lower W/C ratios, the greater concentration of cement particles increased interparticle interactions and internal resistance, resulting in substantially higher yield stress and plastic viscosity. Conversely, increasing the W/C ratio progressively reduced both rheological parameters and enhanced grout mobility. This pattern was particularly evident when the W/C ratio increased from 0.6 to 1.5, with the fitted Bingham equations showing a marked reduction in both the intercept, representing yield stress, and the slope, representing plastic viscosity. At W/C = 0.6, the fitted equation was $\tau = 9.609 + 0.0433\dot{\gamma}$ with $R^2 = 0.9812$, whereas at W/C = 1.5 the equation declined to $\tau = 0.1824 + 0.0093\dot{\gamma}$ with $R^2 = 0.8952$. The highest goodness of fit was obtained for W/C = 0.8 ($R^2 = 0.9949$), followed by W/C = 1.00 ($R^2 = 0.9881$) and W/C = 0.6 ($R^2 = 0.9812$). Although the coefficients of determination were somewhat lower at W/C ratios of 1.2 and 1.5, the overall response remained compatible with Bingham-type behavior. These findings confirmed that variations in W/C ratio directly changed the rheological resistance of the grout and, consequently, its capacity to enter and propagate through the interconnected pore spaces of the tested soils.

Table 2. Bingham rheological equations for cement grout at different water-to-cement ratios

W/C ratio	Bingham equation	Yield stress, τ_0 (Pa)	Plastic viscosity coefficient	R^2
0.6	$\tau = 9.609 + 0.0433\dot{\gamma}$	9.609	0.0433	0.9812
0.8	$\tau = 2.1659 + 0.0205\dot{\gamma}$	2.1659	0.0205	0.9949
1.00	$\tau = 1.0243 + 0.0113\dot{\gamma}$	1.0243	0.0113	0.9881
1.20	$\tau = 0.7111 + 0.0099\dot{\gamma}$	0.7111	0.0099	0.8287
1.50	$\tau = 0.1824 + 0.0093\dot{\gamma}$	0.1824	0.0093	0.8952

Note. τ = shear stress; $\dot{\gamma}$ = shear rate; the intercept represents yield stress and the slope represents the plastic-viscosity component of the Bingham model.

Mixing duration also influenced grout homogeneity and the stability of the measured rheological response. At relatively short mixing times, the cement particles were not uniformly dispersed throughout the suspension, producing noticeable fluctuations in viscosity and other rheological characteristics. With continued mechanical mixing, particle dispersion became more uniform and rheological measurements stabilized. On the basis of the experimental observations, approximately 15 min was identified as an appropriate mixing duration for the grout volume employed in the laboratory program. Figure 5 illustrates the changes in grout viscosity associated with mixing duration. Grout

stability showed an inverse relationship with the water-to-cement ratio. Dense mixtures containing less water exhibited greater resistance to sedimentation; in particular, the $W/C = 0.6$ mixture showed minimal settlement and comparatively favorable stability. As the ratio increased beyond approximately 1.0, particle sedimentation and separation of the grout components became increasingly evident. Thus, the same increase in water content that improved flowability and penetrability also reduced suspension stability, revealing a clear trade-off between rheological mobility and resistance to segregation.

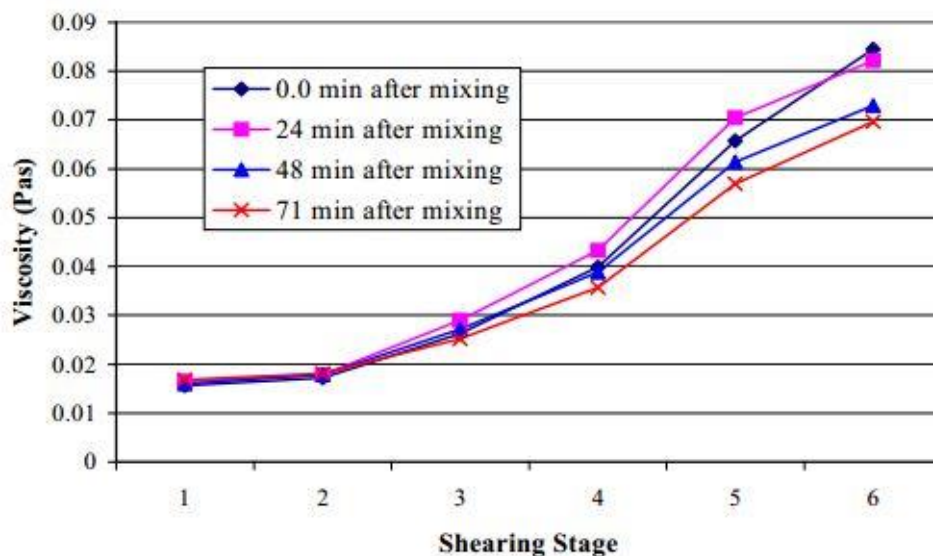


Figure 5. Effect of mixing time on grout viscosity.

3.2. Soil Permeability, Groutability, and Flow Behavior

The permeability experiments showed that the hydraulic conductivity of the tested sandy soils was strongly dependent on fines content, pore structure, and gradation characteristics. An increase in fines content substantially reduced permeability because fine particles occupied the voids between coarser grains, decreased the effective dimensions of the interconnected pore channels, increased hydraulic resistance, and generated more tortuous flow paths. A decrease in void ratio produced a similar effect because consolidation reduced available pore volume and restricted the cross-sectional area through which water or grout could migrate. The uniformity coefficient also affected permeability; soils containing a wider distribution of particle

sizes tended to exhibit lower permeability because smaller particles filled the spaces between larger grains. The trend shown in Figure 6 therefore revealed a pronounced reduction in the measured coefficient of permeability with increasing fines content. Evaluation against the Kozeny–Carman relationship indicated comparatively close agreement for specimens containing relatively small proportions of fines, whereas the discrepancy between measured and theoretically estimated permeability increased as the fines fraction became larger. Accordingly, the experimental results indicated that conventional permeability relationships became progressively less representative of the hydraulic behavior of the reconstructed soils as their fines contents increased.

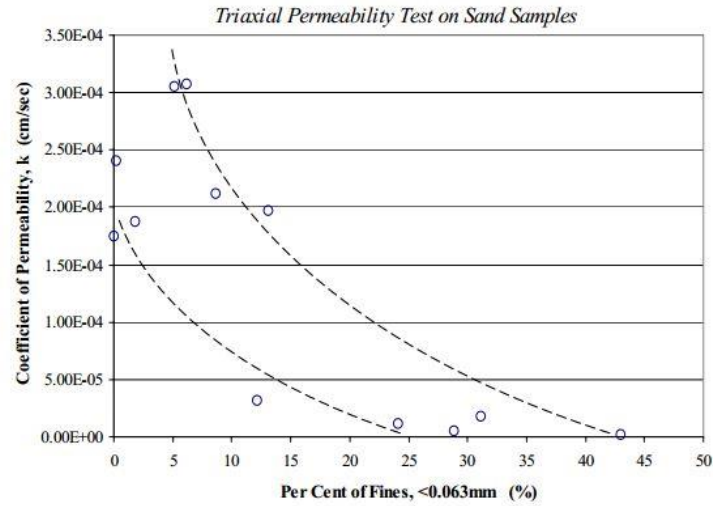


Figure 6. Variation of permeability with fines content.

Groutability measurements confirmed that the water-to-cement ratio was one of the principal variables governing the ability of cement grout to permeate the soil matrix. Increasing W/C reduced yield stress and viscosity and simultaneously increased grout-flow velocity and penetrability. At lower ratios, particularly for the denser mixtures, the greater internal resistance of the cement suspension restricted its movement through small pore throats and increased the hydraulic gradient required to produce a given flow velocity. Figure 7 demonstrates that the relationship between hydraulic gradient (i) and grout-flow velocity (v) varied systematically among the tested W/C ratios and was generally nonlinear. Across the experimental range of W/C = 0.6–1.5, the response depended simultaneously on grout viscosity and injection

pressure rather than conforming to a single Darcy-type proportional relationship. Under the reported low-pressure condition, the hydraulic-gradient–velocity response could be approximated by the linear relationship $i = 287.85v$, with $R^2 = 0.8467$. Under the reported high-pressure condition, however, a nonlinear power relationship provided a substantially stronger fit, $i = 1773.9v^{1.5152}$, with $R^2 = 0.9944$. These results indicate that the grout-flow response deviated increasingly from simple linear Darcy behavior as injection intensity and flow velocity increased. The original experimental description reported linear behavior under low water-flow pressure below 100 kPa and nonlinear behavior at injection pressures above 1 bar, attributing the latter pattern to elevated flow velocity and the development of non-Darcy flow conditions.

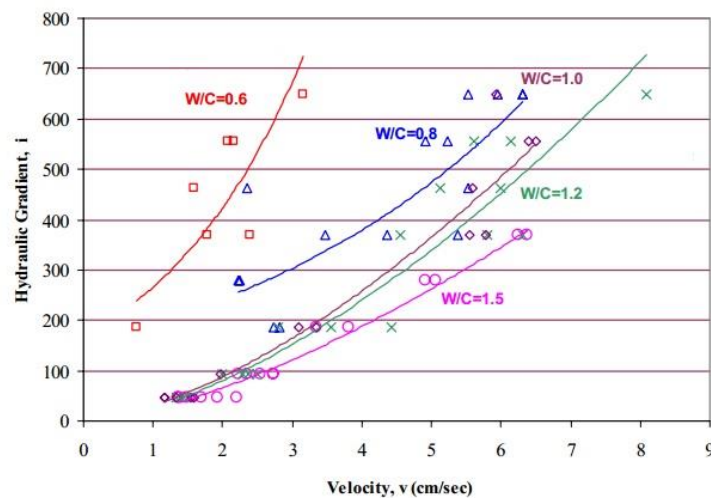


Figure 7. Nonlinear relationship between hydraulic gradient (i) and grout-flow velocity (v) at different water-to-cement ratios.

Table 3. Experimental hydraulic-gradient–flow-velocity relationships

Flow condition	Relationship	R ²	Observed behavior
Low injection pressure	$i = 287.85v$	0.8467	Approximately linear
High injection pressure	$i = 1773.9v^{1.5152}$	0.9944	Nonlinear

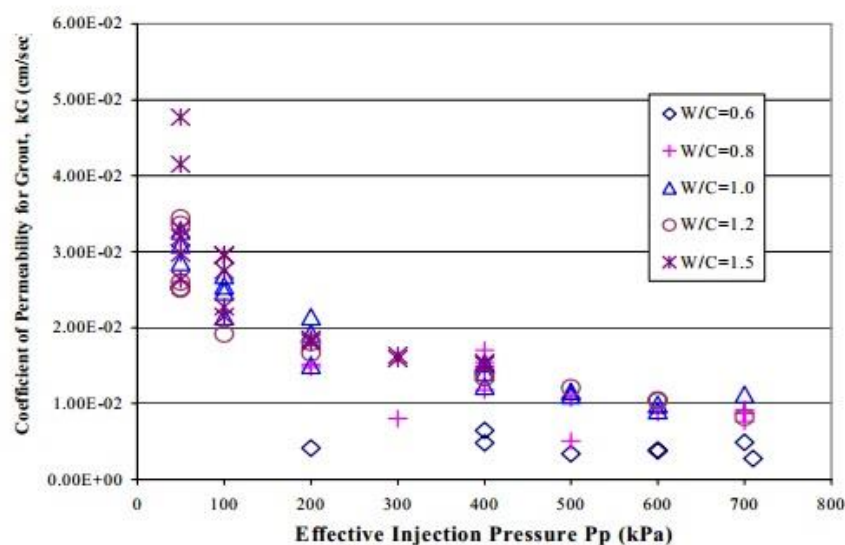
Note. i = hydraulic gradient; v = grout-flow velocity. The source reports the low-pressure condition as below 100 kPa and the high-pressure condition as above 1 bar.

Injection pressure produced a positive but distinctly nonlinear effect on grout discharge. At relatively low pressures, increasing injection pressure resulted in a pronounced increase in grout-flow rate. As pressure continued to rise, however, the incremental increase in flow became progressively smaller, indicating that pressure alone could not indefinitely improve grout propagation. This reduction in pressure sensitivity at the higher end of the investigated range showed that grout viscosity increasingly became the limiting factor controlling movement through the porous medium. Consequently, mixtures with comparatively high viscosity could not be made equivalently penetrable simply by increasing injection pressure, whereas adjustment of the W/C ratio produced a more direct modification of the rheological resistance to flow. The combined results therefore showed that penetrability was governed by the interaction of pressure, grout composition, and soil pore characteristics rather than by injection pressure considered in isolation.

3.3. Grout Permeability Coefficient and Development of the Design Model

The grout permeability coefficient (K_G) was determined from the chamber tests under different combinations of grout

composition and injection condition. The experimental values demonstrated that K_G was strongly dependent on the rheological characteristics of the grout and changed systematically with the water-to-cement ratio. As W/C increased and the cement suspension became less viscous, K_G increased, indicating greater capacity for grout transmission through the soil pore network. In contrast, low-W/C mixtures with high yield stress and plastic viscosity exhibited smaller K_G values and greater resistance to propagation. Figure 8 presents the experimental relationship among K_G , effective injection pressure, and water-to-cement ratio. The plotted results further showed that the effect of increasing pressure was not uniform throughout the pressure range. At lower effective injection pressures, relatively pronounced differences in K_G occurred among grout mixtures, whereas at higher pressures the rate of improvement associated with increasing pressure diminished. These observations were consistent with the flow measurements showing that grout viscosity became increasingly influential once a sufficient pressure level had been reached. Accordingly, K_G provided an integrated hydraulic indicator through which the effects of grout rheology and injection conditions could be incorporated into the selection of permeation-grouting parameters.


Figure 8. Relationship between K_G , injection pressure, and water-to-cement ratio.

Integration of the rheological, soil-permeability, and permeation-grouting results resulted in the proposed practical design framework shown in Figure 9. The model was constructed around a sequential use of measurable soil and grout characteristics. Soil permeability is first determined to characterize the hydraulic capacity of the porous medium; an appropriate W/C range is then selected with consideration of the required balance between suspension stability and grout penetrability; injection pressure is subsequently chosen according to the soil condition and grout rheology; K_G is estimated under the corresponding condition; and the combined information is finally used to assess whether permeation grouting is feasible. The proposed graphical formulation relates parameter selection to D_{10}/K^2 and the W/C ratio and therefore converts the experimental relationships into a

practical basis for design decisions. Overall, the experimental program demonstrated that an increase in W/C enhanced penetrability by lowering yield stress and plastic viscosity, although this occurred at the expense of suspension stability; soil permeability decreased markedly with increasing fines content and decreasing void space; grout flow became nonlinear under the higher injection conditions; and K_G increased as grout viscosity declined. The resulting model therefore integrates soil gradation and permeability with grout rheological response and injection conditions rather than treating each parameter independently, thereby providing a unified framework for selecting the W/C ratio, injection pressure, and grout permeability characteristics for permeation-grouting applications.

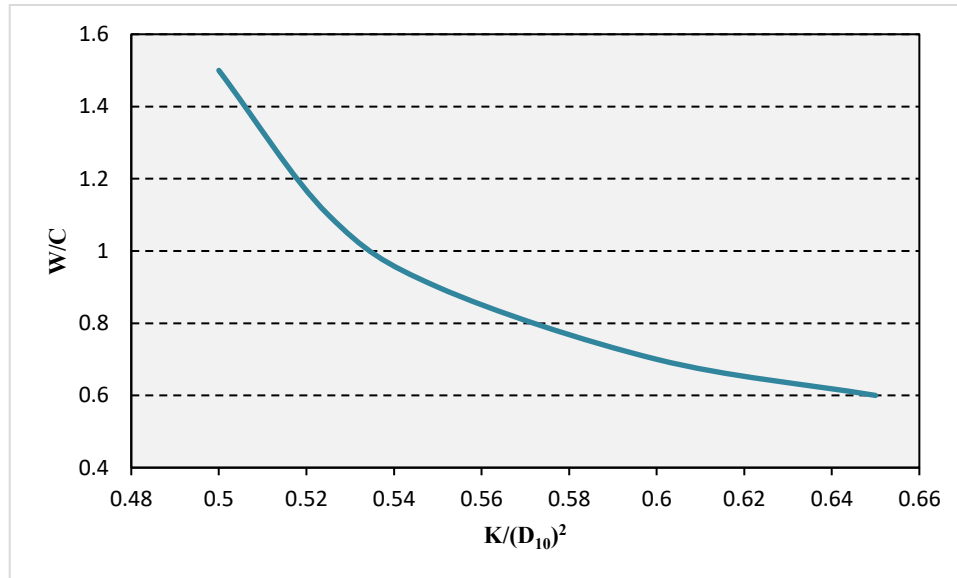


Figure 9. Proposed design model for selecting injection parameters and determining the appropriate water-to-cement ratio based on D_{10}/K^2 .

4. Discussion and Conclusion

The present study investigated the interaction between cement-grout rheology, soil permeability, water-to-cement ratio, injection pressure, and grout permeability coefficient in order to develop a practical framework for permeation-grouting design. The findings showed that all tested cement-grout mixtures behaved as non-Newtonian Bingham fluids, with rheological properties varying systematically as a function of the water-to-cement ratio. The fitted equations demonstrated that increasing the W/C ratio from 0.6 to 1.5 substantially reduced both yield stress and plastic viscosity. For W/C = 0.6, the fitted relationship was $\tau = 9.609 +$

$0.0433\dot{\gamma}$ with $R^2 = 0.9812$, whereas at W/C = 1.5 the relationship decreased to $\tau = 0.1824 + 0.0093\dot{\gamma}$ with $R^2 = 0.8952$. This result indicates that relatively dense cement suspensions require a larger initial stress to initiate movement and continue to exhibit higher internal resistance after yielding. In contrast, increasing water content reduces particle concentration and interparticle resistance and therefore improves slurry mobility through the pore network. This interpretation is consistent with studies showing that cement-based and cement-bentonite grouts exhibit rheology-dependent penetration and that reductions in yield stress and viscosity improve diffusion in granular media [9]. Similar observations have been reported in

research on Bingham-fluid infiltration through porous media, where the rheological parameters of the injected slurry directly govern penetration distance and required injection pressure [6]. The present results therefore support the view that the grout cannot be adequately characterized as a Newtonian liquid and that its yield stress and plastic viscosity should be explicitly considered in permeation-grouting analysis.

The results also revealed an important relationship between grout flowability and stability. Although increasing the W/C ratio improved penetrability, lower W/C ratios produced more stable suspensions with less sedimentation. At W/C = 0.6, the grout exhibited comparatively favorable stability, whereas at ratios greater than 1.0 the tendency toward particle settlement and component separation increased. Thus, the selection of grout composition involves a balance between two competing engineering requirements: sufficient fluidity to permit penetration and sufficient stability to maintain homogeneity during injection. This trade-off is consistent with broader grout-mixture research showing that fresh-state flow properties and stability are highly sensitive to mixture proportions [13]. Optimization studies for shield-tunnel grouts have similarly emphasized that a technically acceptable mixture cannot be selected on the basis of flowability alone because excessive fluidity may compromise segregation resistance and other performance characteristics [14]. Investigations of alternative slurry materials, including modified sodium bentonite and recycled silty-clay slurry, also demonstrate that transport performance depends on the balance between suspension stability, viscosity, and the capacity of particles to remain distributed during movement through confined spaces [15, 17]. Accordingly, the current study indicates that increasing W/C is beneficial only up to the point at which loss of stability becomes operationally significant.

Mixing time was another factor affecting the measured rheological behavior. Short mixing durations resulted in nonuniform particle distribution and greater fluctuations in viscosity, whereas longer mixing improved dispersion and stabilized the measured parameters. Approximately 15 minutes was identified as an appropriate mixing duration for the tested volume. This finding is important because the rheological condition of grout at the moment of injection is partly determined by its preparation history. Studies of shield-tunnel grouting have shown that grout parameters can vary with elapsed time and mixing conditions, thereby influencing subsequent flow and placement behavior [10]. Likewise, comparisons between time-dependent-viscosity

slurries and cement-clay systems have demonstrated that temporal changes in rheology can alter diffusion and anti-seepage performance [11]. Theoretical modeling of time-varying slurry has further shown that incorporating rheological evolution provides a more realistic representation of slurry migration than assuming constant parameters throughout the injection process [12]. The implication is that laboratory and field characterization should be standardized with respect to mixing duration and test timing, because otherwise the measured viscosity and yield stress may not accurately represent the grout during actual injection.

The soil-permeability results showed that fines content was one of the strongest controls on hydraulic conductivity. As the proportion of fines increased, effective pore size decreased, flow paths became more tortuous, and hydraulic resistance increased, leading to a marked reduction in permeability. A reduction in void ratio produced a similar decrease because consolidation reduced the available pore volume. The uniformity coefficient also influenced permeability, as well-graded materials permitted smaller particles to occupy the voids between larger grains. These findings are consistent with theoretical and experimental studies demonstrating that pore structure and grain-size distribution are decisive factors in grout transport through porous media. Xie et al. showed that the diffusion radius of cement-based grouts depends strongly on pore characteristics and that ignoring pore-scale geometry can lead to inaccurate predictions of slurry propagation [5]. Xu et al. similarly demonstrated that particle-size distribution affects the infiltration behavior of Bingham fluids because it determines pore-throat dimensions and hydraulic resistance [6]. Research incorporating tortuosity into permeation-grouting models has also demonstrated that the effective diffusion path can differ substantially from an idealized straight pathway, thereby modifying both pressure demand and penetration distance [7, 8]. The present findings reinforce these conclusions by showing experimentally that permeability cannot be inferred solely from coarse grain-size indicators when appreciable fines are present.

The comparison with the Kozeny–Carman relationship further demonstrated that classical hydraulic formulations were more suitable for soils containing relatively low fines contents than for soils with substantial fines. As the proportion of fines increased, the discrepancy between measured and calculated permeability became larger. This deviation is reasonable because classical relationships generally assume simplified pore geometry and hydraulic

behavior that become increasingly unrealistic in heterogeneous soils with constricted pore throats and complex flow paths. Similar limitations have motivated recent grouting studies to incorporate tortuosity, diffusion-path effects, and filtration into their analytical frameworks [21, 22]. The modified permeation-diffusion model proposed by Song et al., for example, accounts for deep-bed filtration and recognizes that particle retention can alter the effective pore structure during grout movement [23]. Such mechanisms are particularly relevant to cement suspensions, because cement particles may be retained or accumulated within narrow pores and thereby progressively modify the hydraulic conductivity of the medium. The present results therefore support the use of experimentally measured soil permeability, rather than exclusive reliance on classical empirical relationships, when designing grout injection in soils containing notable fines fractions.

A central finding of the study was that water-to-cement ratio was the dominant parameter controlling groutability. Increasing W/C reduced yield stress and viscosity and increased flow velocity and penetration capacity. At lower W/C ratios, internal resistance was sufficiently high that grout movement through small pore spaces became difficult even when pressure was increased. This result is consistent with experimental research on cement-bentonite slurry, which has shown that lower rheological resistance generally improves permeation behavior and reinforcement effectiveness [9]. Investigations of infiltration grouting in heterogeneous moraine deposits have likewise demonstrated that injectability is governed jointly by pore dimensions and slurry properties rather than by particle-size criteria alone [4]. Similar conclusions can be drawn from studies of specialized grout systems, where modification of fluidity and diffusion characteristics has been used to improve penetration performance [27]. The present findings therefore confirm that W/C is not merely a mixture-design parameter but a primary control on the hydraulic interaction between grout and soil.

The relationship between hydraulic gradient and grout-flow velocity was another important result. Under lower injection conditions, the relationship was approximately linear and could be represented by $i = 287.85v$ with $R^2 = 0.8467$. Under higher injection conditions, however, the response became distinctly nonlinear and was better represented by $i = 1773.9v^{1.5152}$ with $R^2 = 0.9944$. This transition indicates that grout flow does not consistently obey Darcy's law over the entire range of injection conditions. Because cement grout has yield stress and non-

Newtonian viscosity, the hydraulic gradient must first overcome a rheological threshold, and the relationship between pressure and velocity may change as flow intensity increases. This finding is consistent with theoretical work on Bingham-grout penetration, in which nonlinear pressure-flow relationships arise naturally from the rheological properties of the slurry [6, 8]. Research on seepage grouting that incorporates realistic diffusion paths has similarly demonstrated that classical linear flow assumptions can be inadequate for predicting slurry migration [21]. Furthermore, models accounting for tortuosity and columnar or spherical diffusion show that flow geometry itself may introduce additional nonlinearities [7, 24]. The strong fit of the nonlinear high-pressure relationship in the present study therefore provides further evidence that design based solely on Darcy-type proportionality may underestimate the complexity of cement-grout transport.

The effect of injection pressure was positive but nonlinear. Increasing pressure produced a substantial increase in flow rate at lower pressure levels, but the incremental gain diminished at higher pressures. This suggests that once sufficient pressure is available to overcome the initial yield and hydraulic resistance, grout viscosity increasingly becomes the dominant limitation. Consequently, simply applying greater injection pressure cannot fully compensate for an unsuitable grout composition. This interpretation is consistent with studies of high-pressure cyclic grouting, which indicate that pressure can improve distribution and reinforcement but must be matched to the rheological and mechanical characteristics of the treated ground [18]. Studies of high-pressure jet-disturbance grouting also demonstrate that changes in pressure can substantially alter diffusion behavior, although excessive pressure may change the treatment mechanism from permeation toward disturbance or displacement [19]. The potential for hydraulic instability is particularly important in fine sandy soils, where high gradients may initiate seepage failure or particle rearrangement [20]. Thus, the present results support selection of injection pressure as part of an integrated grout-soil design rather than as an independent variable to be maximized.

The behavior of the grout permeability coefficient K_G provided an additional basis for this integrated interpretation. K_G increased with increasing W/C ratio and was strongly influenced by grout viscosity. Lower-viscosity mixtures showed greater capacity for transport through the soil, whereas more concentrated mixtures exhibited smaller K_G values. This result is consistent with the general principle

that slurry transmissivity through porous media is governed by both the hydraulic characteristics of the medium and the rheological resistance of the grout. Studies of grout diffusion in gravel-pebble layers and other granular formations likewise show that injection performance depends on the combined effects of slurry characteristics, pressure, and ground structure [26]. Quantitative grouting design in sand layers has similarly emphasized the importance of integrating formation parameters with grout and injection variables rather than relying on isolated empirical indices [25]. The usefulness of K_G in the present study lies precisely in this integrative function: it provides a practical parameter through which the rheological behavior of grout can be related to its movement through a particular porous medium.

The proposed design model synthesizes these findings by linking soil permeability, W/C ratio, injection pressure, and K_G in a sequential decision framework. This approach is consistent with the broader movement in grouting research toward quantitative design and mechanistically informed parameter selection [25]. Numerical reviews of foundation grouting have emphasized that predictive accuracy improves when soil properties, grout behavior, and injection conditions are incorporated simultaneously into design models [3]. The same principle applies to alternative grouting materials, where the engineering performance of geopolymer, bentonite, silicate, or composite slurries depends on matching their transport properties to the treated formation [16, 30]. Research on slurry lubrication and filter-cake formation also demonstrates that flow and plugging behavior are inseparable from the interaction between material properties and surrounding strata [28, 29]. Overall, the current results support a design philosophy in which the permeability of the soil is first characterized, the grout composition is then selected to achieve an appropriate balance between penetrability and stability, and injection pressure is subsequently adjusted within a range compatible with both grout rheology and soil hydraulic response. Such an approach reduces dependence on trial-and-error selection and provides a more physically meaningful basis for permeation-grouting design.

The present study was conducted under controlled laboratory conditions using reconstructed sandy soils and a specific ordinary Portland cement grout system; consequently, the results should be generalized cautiously to field formations characterized by natural layering, anisotropy, irregular pore structures, organic matter, cementation, or discontinuities. The investigated W/C ratios and injection-pressure conditions also represented a defined

experimental range and did not encompass all combinations that may occur in practice. Temperature, chemical composition of groundwater, cement type, particle-size distribution of cement, hydration time, and long-term changes in grout properties were not systematically varied. In addition, the proposed design model was derived primarily from laboratory-scale permeability and chamber tests, and scale effects may influence the pressure distribution, diffusion geometry, filtration behavior, and grout consumption observed in full-scale applications.

Future studies should validate the proposed model using semi-field and full-scale grouting trials in natural sandy deposits with different fines contents and degrees of saturation. Broader experimental programs could investigate additional cement types, ultrafine cements, mineral additives, superplasticizers, bentonite-modified grouts, and environmentally sustainable binders to determine whether the same design framework can be extended to other rheological systems. The effects of grout temperature, elapsed time after mixing, groundwater chemistry, soil anisotropy, and degree of saturation should also be examined systematically. Coupled numerical models calibrated against the present experimental relationships could be developed to predict three-dimensional grout propagation, filtration, pore blocking, and pressure dissipation. Further work should also establish statistically validated relationships for K_G across wider ranges of soil gradation and grout composition and examine the scale dependence of the proposed D_{10}/K^2 -based design relationship.

For practical permeation-grouting projects, soil permeability and gradation should be measured directly before selecting grout composition or injection pressure. The water-to-cement ratio should be chosen by balancing penetrability against suspension stability rather than by maximizing fluidity alone, and grout should be mixed under standardized conditions to ensure consistent rheological properties during injection. Injection pressure should be increased progressively and monitored together with flow rate because a diminishing increase in discharge may indicate that grout viscosity, rather than insufficient pressure, has become the controlling factor. Excessive pressure should be avoided where it may induce hydraulic fracturing, ground disturbance, or a change from permeation to displacement grouting. Whenever possible, trial injections should be used to estimate K_G and verify the predicted groutability before full-scale treatment, and field quality control should include monitoring of grout consistency,

mixing time, pressure, flow rate, injected volume, and evidence of unexpected ground response.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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