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FY26 Task 6: Simulant and Actual Waste Blending and GFC Addition

August 2026

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U.S. DEPARTMENT of ENERGY

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Acronyms and Abbreviations

BNI	Bechtel National, Inc.
DFHLW	Direct Feed High-Level Waste
DI	deionized water
DOE	U.S. Department of Energy
GFC	glass forming chemical
N_{JS}	just-suspended impeller speed
NQAP	Nuclear Quality Assurance Program
PNNL	Pacific Northwest National Laboratory
QA	Quality assurance
RPM	revolutions per minute
SE	southeast
WTP	Hanford Tank Waste Treatment and Immobilization Plant
wt%	weight percent

Quality Assurance

This work was performed in accordance with the Pacific Northwest National Laboratory (PNNL) Nuclear Quality Assurance Program (NQAP). The NQAP complies with the DOE Order 414.1D, *Quality Assurance*, and 10 CFR 830, Subpart A, *Quality Assurance Requirements*. The NQAP uses NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Applications*, as its consensus standard and NQA-1-2012, Subpart 4.2.1, as the basis for its graded approach to quality. The NQAP works in conjunction with PNNL's laboratory-level Quality Management Program, which is based on the requirements as defined in the DOE Order 414.1D and 10 CFR 830, Subpart A.

The work of this report was performed at a technology readiness level of 5, the highest level of applied research under NQAP.

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1.0 Introduction

The Hanford Site holds over 50 million gallons of radioactive and chemical waste historically stored in 177 underground storage tanks. Current treatment plans call for immobilization of the high-level radioactive fraction of this waste through vitrification at the Hanford Waste Treatment and Immobilization Plant (WTP). Historically, treatment strategies relied on extensive pretreatment operations to separate and condition waste streams prior to vitrification. More recently, the DOE has evaluated Direct Feed High-Level Waste (DFHLW) processing, in which selected high-level waste streams are transferred directly to the High-Level Waste Facility for blending with glass-forming chemicals (GFCs) and vitrification without undergoing the full pretreatment flowsheet (DOE, 2023).

Successful implementation of DFHLW requires reliable mixing, transfer, and handling of both waste slurries and melter feeds. The physical and chemical diversity of Hanford tank waste can produce a wide range of transport-related behaviors, including differences in settling, rheology, sediment strength, and solids suspension requirements. These properties influence waste retrieval, blending, vessel mixing, pipeline transport, and melter feed preparation operations (Reynolds, 2006). Consequently, understanding how waste composition affects transport behavior is important for identifying waste streams that may present operational challenges and for developing strategies to mitigate those challenges before processing begins.

As part of a multi-year effort to support DFHLW planning and flowsheet development, actual Hanford Southeast (SE) quadrant wastes were previously composited into five representative waste groups enriched in aluminum (Al), iron (Fe), phosphate (PO_4), uranium (U), and zirconium (Zr) (Daniel et al. 2026). These composites were generated from archived core samples obtained from Tanks AN-101, AN-106, and AW-105 and were intended to represent distinct waste chemistries expected to be encountered during future DFHLW operations. Comprehensive characterization of the composites included measurements of settling behavior, rheology, shear strength, particle size, and just-suspended impeller speed (N_{JS}). Daniel et al. (2026) reported that the Fe-rich composite exhibited non-Newtonian behavior, slow settling rates, and elevated N_{JS} values relative to the other waste types, indicating that these materials may present greater challenges for mobilization, suspension, and transport operations. In contrast, the Al-rich composite displayed more favorable suspension characteristics and lower N_{JS} requirements.

The results of the baseline characterization study identified the Fe-rich composite as a waste form of particular interest for subsequent investigation. Although the Fe-rich material settled slowly and exhibited relatively low settled-bed shear strengths, its non-Newtonian rheology and elevated N_{JS} suggested the formation of structured particle networks that resisted mobilization and suspension. These characteristics may complicate waste blending, transfer, and feed preparation operations and warranted further evaluation of potential approaches for modifying or mitigating the observed transport behavior.

Because the quantity of actual Hanford waste available for experimentation is extremely limited and blending of actual waste composites is irreversible, a staged experimental strategy was adopted. Prior to consuming valuable actual waste samples, non-radioactive simulants were developed to reproduce the transport-related behavior observed in the Fe-rich and Al-rich composites. The use of simulants provided a mechanism to evaluate potential blending and remediation strategies while preserving the finite inventory of actual waste material. Equally important, the simulant studies provided an opportunity to determine whether the transport behaviors observed in the actual waste composites could be reasonably reproduced in a non-radioactive system.

The first phase of the study focused on development of representative Fe-rich and Al-rich simulants and evaluation of their settling behavior, shear strength, and N_{JS} characteristics. Simulant formulations were adjusted and characterized to determine whether they reproduced the key transport behaviors observed

during actual waste testing. Once representative simulants were established, Fe-rich and Al-rich simulants were blended at varying ratios to evaluate whether the favorable transport characteristics associated with Al-rich material could improve the suspension and mobilization behavior of Fe-rich slurries. The resulting trends were subsequently compared with analogous blending studies performed using actual Fe-rich and Al-rich waste composites to assess the predictive capability of the simulants and to determine whether blending represents a viable strategy for modifying transport behavior.

In parallel with the blending studies, the impact of GFC additions on slurry transport properties was investigated. Previous compositional evaluations indicated that the PO_4-rich and U-rich composites require substantially larger quantities of GFCs than other waste types to produce acceptable high-level waste glass formulations. Consequently, the resulting melter feeds may contain significantly greater solids inventories and exhibit problematic transport behaviors.

To evaluate these effects, GFCs were added to the PO_4-rich, U-rich, and Fe/Al blended waste systems at ratios corresponding to projected glass formulations and waste loadings. Initial samples were prepared by adding glass formers in appropriate ratio to the composition of the waste oxides in the sample (Vienna et al. 2022 and Hrma et al. 1994). This resulted in samples that were outside the operating envelope for the Waste Treatment Plant. These samples were then diluted so that they resided inside the planned WTP operating envelope. These tests were intended to demonstrate the physical characteristics of the slurries at their true projected glass yields and to identify potential challenges associated with mixing, suspension, and transport of the resulting melter feeds.

The overall objective of this work is to establish the relationship between waste composition, blending strategy and glass-former addition on slurry properties including rheology, strength and mobilization for representative Hanford SE Quadrant wastes. The resulting data provides a basis for evaluating the representativeness of simulants, assessing potential waste blending strategies, and understanding the transport implications of planned DFHLW melter feed formulations.

2.0 Materials and Methods

The testing described herein was designed to evaluate the effects of waste composition, blending strategy, and glass-forming chemical addition on transport related properties relevant to DFHLW. Testing was performed using both non-radioactive simulants and actual Hanford waste composites and included measurements of settling behavior, settled solids properties, shear strength, rheology, and just-suspended impeller speed (N_{JS}). The following sections describe preparation of the simulants and waste blends as well as the experimental methods used to characterize slurry transport behavior.

2.1 Experimental Approach

This study was conducted as a continuation of the Year 1 Task 5: *Compositing and Characterization of SE Quadrant Waste Exemplars* efforts reported by Daniel et al. (2026). Previous characterization of actual Hanford waste exemplars identified significant differences in settling behavior, rheology, and solids suspension characteristics among Al-rich, Fe-rich, PO_4-rich, U-rich, and Zr-rich waste composites. In particular, the Fe-rich composite exhibited slow settling behavior, non-Newtonian rheology, and elevated just-suspended impeller speeds (N_{JS}), indicating transport behaviors that may present challenges during DFHLW operations.

To investigate potential approaches for modifying these transport characteristics while minimizing consumption of limited actual waste samples, a staged experimental program was performed. The study consisted of four primary activities:

1. Development and evaluation of Fe-rich and Al-rich simulants representative of previously characterized actual waste composites.

2. Blending studies using Fe-rich and Al-rich simulants to assess the impact of compositional blending on settling and suspension behavior.

3. Confirmation testing using blends prepared from actual Fe-rich and Al-rich waste composites.

4. Evaluation of GFC additions to blended waste systems and to PO_4-rich and U-rich waste composites representative of projected DFHLW melter feeds.

Settling behavior, settled solids characteristics, shear strength, and N_{JS} were measured throughout the study to evaluate the effects of composition, blending, and glass former addition on transport-related properties.

2.2 Waste Composites and Simulants

Actual waste composites used in this study were derived from the southeast (SE) Quadrant waste exemplars previously prepared from archived Hanford tank waste samples obtained from Tanks AN-101, AN-106, and AW-105. The waste exemplars consisted of composite materials enriched in aluminum, iron, phosphate, uranium, and zirconium chemistries and were previously characterized for physical and chemical properties.

To preserve the limited inventory of actual waste material, non-radioactive simulants representing the Fe-rich and Al-rich waste composites were prepared and evaluated prior to performing irreversible blending studies using actual waste samples. Simulant compositions were selected based on the measured chemistry and physical behavior of the corresponding actual waste composites. Simulants were prepared

in a nominal Hanford tank waste supernatant solution and adjusted to target solids concentrations representative of the actual waste systems. In addition to the surrogate studies, selected blending and glass former addition experiments were subsequently performed using actual Hanford waste composites. Actual waste testing was conducted to determine whether the trends observed during surrogate development and blending studies were representative of actual waste behavior and to evaluate the applicability of the surrogate materials for predicting transport related properties. Comparisons between surrogate and actual waste systems focused on settling behavior, settled solids characteristics, shear strength, rheological properties, and N_{JS} testing.

2.3 Fe-Rich Surrogate Development

Initial testing focused on development of a non-radioactive simulant capable of reproducing the transport related behavior observed in the actual Fe-rich waste composite. Previous characterization of the actual waste composite demonstrated slow settling behavior, elevated N_{JS}, and non-Newtonian rheological characteristics. Because the quantity of actual waste available for testing was limited, development of a representative simulant was necessary prior to conducting extensive blending remediation studies.

A precipitated Fe-rich hydroxide sludge that has been developed and utilized in previous Hanford waste studies (Westesen et al. 2023) was selected as the starting material for simulant development. The sludge was prepared by precipitating ferric hydroxides from nitrate solutions followed by incorporation of minor phosphate-, oxalate-, carbonate-, calcium-, magnesium-, and manganese-bearing phases and subsequent washing to remove excess nitrate. This material consistently exhibited the slow settling behavior commonly associated with high-iron waste slurries and therefore provided a suitable foundation for development of an Fe-rich waste surrogate. However, previous testing demonstrated that the precipitated hydroxide sludge possessed relatively little strength and did not exhibit the degree of rheological structure observed in the actual Fe-rich waste composite (Westesen et al. 2023). Consequently, the precipitated sludge alone was not considered sufficiently representative of the actual waste system.

To improve the representativeness of the simulant, reagent-grade iron oxide (Fe_2O_3) was added to the precipitated hydroxide sludge. The working hypothesis was that incorporation of additional iron oxide particles would increase the structural integrity of the solids network while maintaining the slow settling characteristics provided by the precipitated hydroxide matrix. A series of simulant formulations spanning Fe_2O_3-to-sludge solids ratios from 0 to 1 were prepared and subsequently characterized. The objective was to identify a formulation that best reproduced the combined settling, shear strength, rheological, and solids suspension characteristics previously measured for the actual Fe-rich waste composite.

The actual Fe-rich waste composite exhibited a final settled solids concentration of approximately 20 wt%, an apparent viscosity of 24.9 cP at 20 wt% solids, a yield stress of approximately 2.1 Pa, a settled bed shear strength less than 30 Pa, and an N_{JS} of 1210 rpm. These properties were used as target performance metrics during simulant development. The precipitated Fe-rich hydroxide sludge was mixed until homogeneous and combined with measured quantities of Fe_2O_3 and a nominal 5.6 M Na tank waste simulant solution to achieve the target Fe_2O_3-to-sludge ratios shown in Table 2-1 while maintaining total solids concentrations representative of the actual waste system.

Each simulant formulation was subsequently evaluated for settling performance, shear strength measurements, rheological characterization, and N_{JS} testing. The measured properties were compared with those of the actual Fe-rich waste composite to identify formulations that most closely reproduced the observed transport behavior. Based on the combined evaluation of settled solids concentration, rheology, shear strength, and solids suspension performance, formulations TI204-C and TI204-D provided the closest agreement with the actual waste properties. These materials were subsequently blended together to produce slurry TI204-CD, which served as the Fe-rich surrogate for the remainder of the study.

Table 2-1. Actual Waste Composite Surrogate Slurry Candidates

Slurry ID	Target Fe_2O_3:Fe Sludge Ratio	Actual Fe_2O_3:Fe Sludge Ratio	Fe Sludge Solids (wt %)	Fe_2O_3 Solids (wt %)	Total Solids (wt %)
TI204-A	0.00	0.00	17.5	0.00	18.0
TI204-B	0.25	0.27	14.1	3.80	18.0
TI204-C	0.50	0.54	9.70	5.00	15.0
TI204-D	1.00	1.07	7.20	8.00	15.0

2.4 Fe/Al Blending Studies

Following identification of a representative Fe-rich surrogate, blending studies were conducted to evaluate whether the addition of Al-rich solids would improve the transport behavior of Fe-rich waste systems. Previous characterization of the actual SE Quadrant waste exemplars showed that Al-rich composites exhibited lower N_{JS} values and more favorable suspension characteristics than Fe-rich composites. Consequently, blending was investigated as a potential strategy for modifying the transport behavior of challenging Fe-rich waste streams prior to melter feed preparation. The blending ratios were selected to evaluate whether favorable transport characteristics associated with Al-rich waste could progressively remediate the elevated N_{JS} requirements (1210 rpm vs 570 rpm) and non-Newtonian behavior observed for Fe-rich waste composites. The surrogate blending studies served as a screening tool for evaluating potential remediation strategies prior to performing analogous blending experiments using limited actual waste composites.

Rather than preparing multiple independent Fe-Al blends from separate subsamples of TI204-CD, gibbsite [$Al(OH)_3$] was incrementally added to a single slurry inventory between characterization campaigns. This approach minimized sample consumption, provided sufficient material for all planned testing, and allowed gradual evaluation of transport property changes as the aluminum concentration increased. The approach also reduced variability associated with preparing multiple independent batches.

Following each gibbsite addition, the slurry was thoroughly mixed and characterized for settling behavior, solids suspension characteristics, and rheological properties. The amount of gibbsite added was selected to progressively increase the gibbsite-to-Fe solids ratio while maintaining solids concentrations representative of projected waste processing conditions. The resulting blend compositions are summarized in Table 2-2.

Table 2-2. Fe-Al Blend Slurries

Slurry ID	Gibbsite Added, g	Total Gibbsite, g	Simulant Added, g	Gibbsite:Fe Ratio	Total Solids, wt %	Gibbsite Mass Fraction, wt %
TI204-CD-1	10.076	10.076	0.00	0.50	19.1	33
TI204-CD-2	10.005	20.081	42.312	1.00	19.4	50
TI204-CD-3	20.009	32.435	120.015	2.60	16.8	72
TI204-CD-4	40.005	72.441	140.020	5.81	19.1	85

2.5 Settling, Shear Strength, and N_{JS} Testing

Settling behavior, settled bed shear strength, rheological properties, and N_{JS} measurements were performed throughout the study to characterize the transport behavior of both non-radioactive surrogate

slurries and actual Hanford waste composites. These measurements were used during surrogate development to identify formulations representative of previously characterized waste exemplars, during Fe/Al blending studies to evaluate the impact of composition on transport behavior, and following glass-forming chemical addition to assess the physical properties of candidate DFHLW melter feeds. Unless otherwise noted, identical testing methodologies were applied to both surrogate and actual waste samples to facilitate direct comparison of transport-related properties.

For settling studies, each slurry was mixed until visually homogeneous and approximately 90 mL of material was transferred to either a 125- or 150-mL graduated cylinder equipped with a centimeter scale. The transfer of slurry to the cylinder marked the start of the settling test. A camera was used to continuously record settling behavior, and the position of the solid-liquid interface was measured periodically throughout the test. Measurements continued until no change in interface height was observed over 12 hours. Initial settling rates were determined based on the solid-liquid interface change during the first 4-12 hours and final settled solids concentrations were calculated from the final settled solids volume and measured solids content of the slurry. Following completion of settling measurements, an aliquot of clarified supernate was collected for density determination using a 5- or 10-mL volumetric flask.

Settled-bed shear strength measurements were performed to quantify the strength of the compacted solids layer following settling. Slurries were homogenized, transferred to test vessels, and allowed to settle quiescently for periods of approximately 24, 48, and 192 hours prior to testing. Shear strength measurements were obtained using a rheometer equipped with a vane geometry. The vane was lowered into the settled solids layer and rotated at a controlled rate while the instrument recorded the resisting torque. The maximum measured torque was converted to settled-bed shear strength using the vane geometry relationship by the instrument software. These measurements were used to evaluate the extent of solids network formation and the force required to remobilize settled solids.

N_{JS} testing was performed using a bench-scale mixing apparatus consisting of a baffled mixing vessel, overhead mixer, impeller, graduated scale, and video recording system. The mixing vessel was mounted on a transparent stand to allow simultaneous observation of solids motion from both the side and bottom of the vessel. Prior to testing, each slurry was homogenized and transferred to the mixing vessel to a nominal slurry depth of 4 cm. The slurry was then allowed to settle overnight to establish a reproducible settled bed. The impeller was positioned such that the bottom edge of the blades was located approximately 2 cm above the vessel floor. Mixing was initiated at 100 rpm and increased in 50-rpm increments at intervals of approximately 2 to 5 minutes. During testing, observations were recorded for the onset of upper-layer solids entrainment, disturbance of solids resting on the vessel floor, and complete solids suspension. The N_{JS} value was defined as the minimum impeller speed at which no stationary solids remained on the vessel bottom and all solids participated in continuous circulation throughout the vessel (Zwietering, 1958 and Paul et al. 2004). N_{JS} measurements were used as a quantitative indicator of slurry suspension difficulty and provided a basis for comparison between surrogate and actual waste systems (Bachman et al. 2025).

2.6 Glass Former Addition Testing

Glass-forming chemical (GFC) addition studies were performed to evaluate the physical properties of candidate DFHLW melter feeds and determine the impact of glass production requirements on transport behavior. Glass formulation evaluations for each actual waste composite material identified the Fe-rich, PO_4-rich, U-rich, Al-rich, and Zr-rich waste composites as having maximum projected waste loadings of approximately 46.2, 22.1, 29.3, 40.1, and 29.4 wt%, respectively. The PO_4-rich and U-rich wastes were selected for further study because they were determined to require substantially larger quantities of GFCs than the other waste types and were therefore expected to produce the most challenging melter feed

compositions. The Fe/Al blended waste sample generated during the blending studies was also evaluated as an opportunistic comparison because sufficient material remained following transport characterization. Although the blended sample was not expected to require the high GFC additions projected for the PO_4-rich and U-rich composites, testing provided an opportunity to compare the physical properties of a blended waste melter feed with those projected for the individual waste composite formulations and assess the impact of blending on subsequent GFC addition requirements.

Initial GFC additions were calculated directly from the projected glass formulations and corresponding waste loading constraints. Glass formers were added in proportion to the waste oxide inventory to produce melter feed compositions representative of the maximum projected waste loading for each waste type. Preliminary calculations indicated that the resulting melter feeds could exhibit glass yields substantially greater than planned operating targets. For example, the projected PO_4-rich formulation was estimated to produce approximately 909 g glass/L feed, significantly greater than the nominal target of approximately 550 g glass/L feed (Reynolds, 2006).

Based on these projections, additional formulations were prepared through controlled dilution with process water to evaluate the impact of glass yield and feed density on transport behavior. Testing targeted glass yields of approximately 750, 625, and 500 g glass/L feed, corresponding to estimated melter feed densities of approximately 1.63, 1.53, and 1.42 g/mL, respectively. These conditions were selected to bound both the nominal melter feed density limit and historical glass yield targets and to evaluate whether reductions in glass production efficiency could provide operations benefits associated with improved slurry handling characteristics.

3.0 Results

The following results detail the testing efforts associated with development of a representative Fe-rich surrogate, followed by surrogate and actual waste Fe/Al blending studies to evaluate the effect of aluminum-bearing solids on transport behavior. Additionally, an examination of the impact of GFC additions on the transport properties of representative DFHLW melter feeds, including the influence of glass yield, dilution, and again on settled bed shear strength was conducted.

3.1 Fe-Rich Surrogate Development

A series of Fe-rich surrogate formulations were prepared by blending varying quantities of Fe_2O_3 with a precipitated Fe-rich hydroxide sludge to reproduce the transport related properties of the actual Fe-rich waste composite. Surrogate performance was evaluated based on comparison with previously measured actual waste properties, including settled solids concentration, shear strength, and N_{JS}. The actual Fe-rich waste composite exhibited a final settled solids concentration of approximately 20 wt%, a settled-bed shear strength less than 30 Pa, and an N_{JS} of 1210 rpm (Daniel et al. 2026).

Initial surrogate screening focused on comparison of final settled solids concentration to the actual Fe-rich waste composite value of 20 wt%. Testing began with TI204-D, which contained the largest ratio of added Fe_2O_3 and was expected to exhibit the highest settled solids concentration of the 4 surrogate blends. TI204-D produced a final settled solids concentration of 21.2 wt%, in good agreement with the actual waste target. Subsequent testing of TI204-C yielded a final settled solids concentration of 16.6 wt%, also reasonably consistent with the observed behavior of the actual waste composite. Because both formulations bracketed the target settled solids concentration and represented the two highest Fe_2O_3 addition levels evaluated, additional settled solids testing was not performed on TI204-A or TI204-B. Instead, subsequent surrogate selection focused on shear strength measurements and practical considerations associated with generating sufficient sample volume for N_{JS} testing and Fe/Al blending studies. Settled-bed shear strength measurements were performed on all surrogate formulations and indicated that each sample remained below the approximately 30 Pa shear strength measured for the actual Fe-rich waste composite. Average measured shear strengths ranged from approximately 2 to 25 Pa, indicating that incorporation of Fe_2O_3 did not result in excessive bed consolidation while maintaining behavior representative of the actual waste system. Based on the combined evaluation of settled solids concentration, shear strength, and the need to generate sufficient material for subsequent N_{JS} and blending studies, formulations TI204-C and TI204-D were identified as the most representative surrogate candidates. A summary table of each surrogate blend results is shown in Table 3-1.

N_{JS} testing was performed only after the TI204-C and TI204-D slurries were combined to produce the TI204-CD surrogate. Because TI204-C and TI204-D both exhibited settled solids concentrations and shear strengths consistent with the actual Fe-rich waste composite, the two formulations were combined to produce the TI204-CD surrogate. Combining the materials generated sufficient sample volume for N_{JS} testing and subsequent Fe/Al blending studies while maintaining a representative Fe-rich surrogate composition. The resulting TI204-CD surrogate exhibited an N_{JS} of approximately 980 rpm, reasonably close to the 1210 rpm measured for the actual Fe-rich waste composite and consistent with the elevated suspension requirements previously observed for the actual Fe-rich waste composite. Based on these results, TI204-CD was selected as the representative Fe-rich surrogate for the Fe/Al blending studies described in the following section.

Table 3-1 Physical Property Measurements for Fe-rich Surrogate Candidates

Sample ID	Settled Solids Concentration, wt%	Shear Strength, Pa	N_{JS}, rpm
TI204-A	--	24.88	--
TI204-B	--	4.23	--
TI204-C	16.6%	1.80	--
TI204-D	21.2%	9.80	--
TI204-CD	--	--	980
Actual Fe-rich Waste	~20%	<30	1210

3.2 Fe/Al Surrogate Blending Studies

Following development of the TI204-CD Fe-rich surrogate, a series of blending studies were performed through incremental addition of gibbsite [$Al(OH)_3$]. The objective of the testing was to determine whether transport characteristics associated with Al-rich waste could improve the challenging suspension behavior observed for Fe-rich waste systems. Four blend composites were prepared containing between 33 and 85 wt% gibbsite on a total solids basis. To isolate the effects of solids composition, all blend formulations were prepared at an initial solids concentration of approximately 20 wt%, allowing differences in settling and suspension behavior to be attributed primarily to changes in the relative proportions of Fe-rich and Al-rich solids. The resulting blends were characterized using settling rate and final settled solids concentration.

Settling results for the Fe/Al surrogate blends are summarized in Table 3-2. Addition of gibbsite resulted in a substantial increase in settling rate relative to the parent Fe-rich surrogate, indicating that incorporation of Al-rich solids promoted more rapid solids segregation. The largest increase in settling rate was observed between TI204-CD-1 and TI204-CD-2, while subsequent increases in gibbsite concentration produced comparatively smaller changes in settling behavior.

A more pronounced trend was observed in the final settled solids concentration. As the gibbsite fraction increased from 33 to 85 wt% of the total solids inventory, the final settled solids concentration increased from 23.6 to 42.2 wt%. Because all blends were prepared at approximately the same initial solids concentration, the increase in final settled solids concentration reflects changes in solids packing behavior associated with increasing gibbsite content rather than differences in initial solids loading. This result indicates that the addition of gibbsite substantially increased the packing efficiency of the settled solids bed and reduced the highly expanded settled structure characteristic of the Fe-rich hydroxide sludge. The progressive increase in settled solids concentration is consistent with the known settling behavior of gibbsite, which forms relatively dense settled beds compared with precipitated iron hydroxide solids.

Collectively, the settling results demonstrate that increasing the fraction of Al-rich solids systematically altered the physical behavior of the surrogate slurry, producing faster settling and substantially greater settled solids consolidation. These observations suggest that blending with Al-rich waste has the potential to significantly modify the transport properties of Fe-rich waste systems and provided the basis for subsequent comparison with actual waste blending experiments.

Table 3-2 Settling behavior of Fe/Al Surrogate Blends

Sample ID	Gibbsite:Fe Ratio	Gibbsite Fraction of Total Solids, %	Initial Solids Concentration, wt%	Settling Rate, cm/hr	Final Settled Solids Concentration, wt%
TI204-CD-1	0.50	33	19.1	0.31	23.6
TI204-CD-2	1.00	50	19.4	0.80	30.7
TI204-CD-3	2.60	72	16.8	0.59	34.3
TI204-CD-4	5.81	85	19.1	0.58	42.2

3.3 Actual Waste Fe/Al Blending Studies

Following completion of the surrogate blending studies, analogous blending experiments were performed using actual Fe-rich and Al-rich waste composites. The objective was to determine whether the trends observed during surrogate testing were representative of actual waste behavior and to evaluate the applicability of the surrogate materials for predicting the effects of blending on transport-related properties. Four blend compositions were prepared containing between 15 and 50 wt% Al-rich solids on a total solids basis while maintaining an initial solids concentration of approximately 20 wt%.

Settling results for the actual waste blends are summarized in Table 3-3 and Figure 3.1. Similar to the surrogate blending study, incorporation of increasing fractions of Al-rich solids produced only modest changes in settling rate. Measured settling rates ranged from approximately 0.27 to 0.36 cm/hr and did not exhibit a strong dependence on blend composition. The settling curves shown in Figure 3.1 indicate that all blends approached their final settled condition within approximately 24 hours, with only minor consolidation occurring thereafter.

Table 3-3 Settling Behavior of Actual Fe/Al Waste Blends

Sample ID	Al:Fe Slurry Composite Ratio	Al-slurry Fraction in Total Solids, %	Initial Solids Concentration, wt%	Settling Rate, cm/hr	Final Settled Solids Concentration, wt%
Blend 1	0.17	14.8	20.0	0.274	29.0
Blend 2	0.32	24.5	19.9	0.358	30.4
Blend 3	0.72	41.8	20.0	0.301	33.3
Blend 4	1.01	50.1	20.0	0.354	35.7

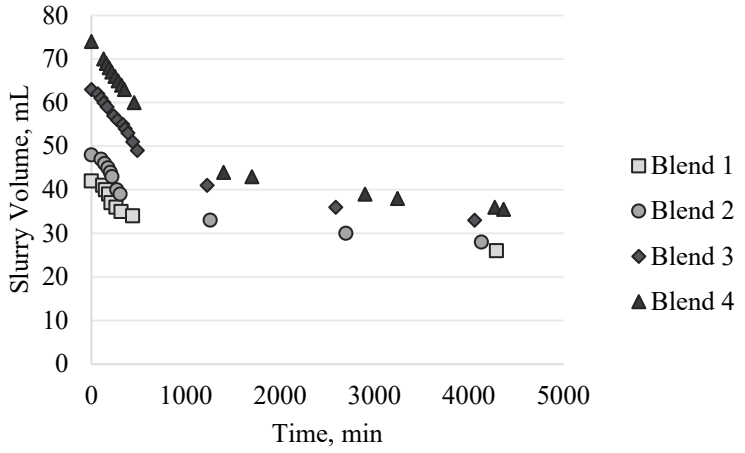


Figure 3.1 Settling Curves of Actual Fe/Al Waste Blends

In contrast, the final settled solids concentration exhibited a strong dependence on blend composition. Seen in Figure 3.2, as the fraction of Al-rich solids increased from 15 to 50 wt% of the total solids inventory, the final settled solids concentration increased from 29.0 to 35.7 wt%. Because all blends were prepared at approximately 20 wt% initial solids concentration, this increase reflects changes in solids packing and consolidation behavior associated with increasing Al-rich solids content rather than differences in initial solids loading.

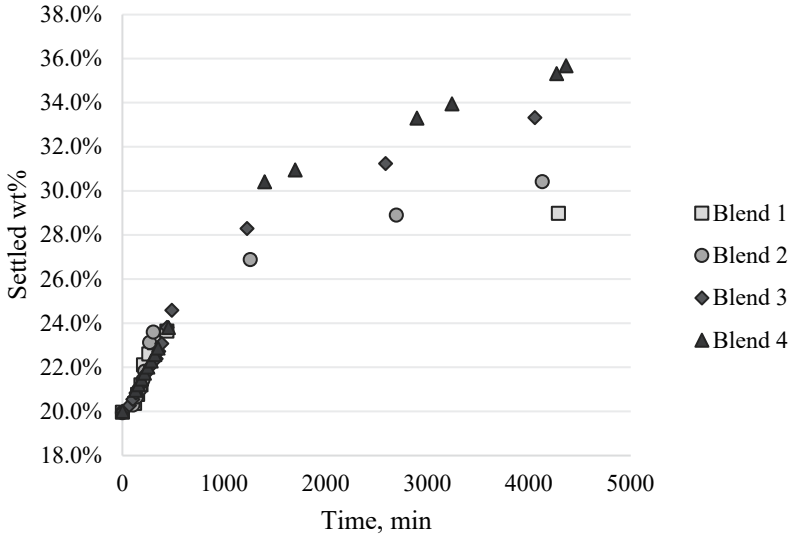


Figure 3.2 Settling Curves of Actual Fe/Al Waste Blends

As shown in Figure 3.3, the final settled solids concentration increased approximately linearly with increasing Al-rich solids concentration, producing a correlation coefficient (R^2) of >0.98. This strong relationship suggests that the settled-bed structure of the blended waste can be reasonably predicted based on the relative proportions of Fe-rich and Al-rich solids. The results indicate that incorporation of Al-rich waste progressively reduces the expanded settled-bed structure characteristic of Fe-rich waste and promotes formation of a denser, more consolidated settled solids layer.

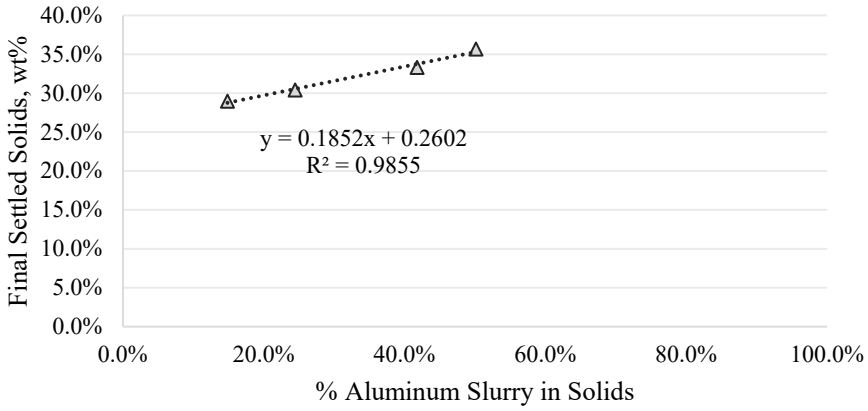


Figure 3.3 Final Settled Solids Concentration Versus % Al Slurry in Solids

The actual waste blending results were consistent with the trends observed during surrogate testing. In both systems, increasing Al-rich solids content produced higher final settled solids concentrations and modest increases in settling rate. Although the actual waste blends exhibited a smaller overall increase in settled solids concentration than the surrogate system, the qualitative agreement between the two datasets suggests that the surrogate materials successfully captured the primary effects of blending on settling behavior and solids consolidation.

Additional characterization was performed on Blend 4, which contained approximately 50 wt% Al-rich slurry and represented the highest Al loading evaluated using actual waste. Settled-bed shear strength measurements yielded an average value of 23.6 Pa, comparable to the 21 Pa measured previously for the Fe-rich waste composite and substantially lower than the 57 Pa measured for the Al-rich waste composite (Daniel et al. 2026). Assuming ideal linear blending of the endmember waste properties, a shear strength of approximately 39 Pa would have been expected. The lower measured value suggests that incorporation of Al-rich waste did not proportionally increase settled-bed strength and that the blended system retained shear characteristics more similar to the Fe-rich waste composite.

N_{JS} testing of Blend 4 yielded a value of 970 rpm. This result represents a substantial reduction relative to the Fe-rich waste composite (1210 rpm), confirming that incorporation of Al-rich waste improved solids suspension behavior by approximately 20%. However, the measured N_{JS} remained significantly greater than that of the Al-rich waste composite (570 rpm). A simple linear interpolation of the waste properties would predict an N_{JS} of approximately 890 rpm for a 50:50 blend. The measured value of 970 rpm indicates that suspension behavior remained more strongly influenced by the Fe-rich component than would be expected based on ideal mixing. These results suggest that while blending with Al-rich waste can partially mitigate the transport challenges associated with Fe-rich waste, the improvement in suspension behavior is less pronounced than predicted by linear averaging of the endmember properties.

3.3.1 Comparison of Surrogate and Actual Waste Blending Behavior

To facilitate direct comparison between the surrogate and actual waste blending studies, the blend compositions were normalized based on the fraction of Al-bearing solids present in each sample. For the surrogate blends, the Al-bearing solids fraction was defined as the mass fraction of gibbsite [$Al(OH)_3$] in the total solids inventory. For actual waste blends, the Al-bearing solids fraction was estimated assuming 62 wt% of the Al-rich composite solids were associated with aluminum-bearing phases based on the composite characterization reported by Daniel et al. (2026).

Figure 3.4 compares settling behavior as a function of Al-bearing solids fraction for the surrogate and actual waste systems. The highest Al-bearing solids fraction data point for the actual waste system corresponds to the Al-rich waste composite characterized by Daniel et al. (2026) and represents a bounding composition containing no Fe-rich waste solids. The remaining actual waste data points correspond to Blend 1 through Blend 4 prepared during the present study.

In both systems, increasing the proportion of Al-bearing solids generally resulted in faster settling behavior relative to the Fe-rich baseline composition. The similarity in the overall trend suggests that the surrogate system successfully captured the qualitative impact of Al-rich solids on slurry settling behavior. While the surrogate correctly predicted the direction of the response, it generally overpredicted the magnitude of the settling rate increase observed in the actual waste blends. At Al-bearing solids fractions greater than approximately 50 wt%, the surrogate blends exhibited settling rates approaching 0.6–0.8 cm/h, whereas the actual waste blends remained closer to 0.3–0.4 cm/h. This difference likely reflects the simplified composition of the surrogate system, which consisted primarily of precipitated Fe hydroxide and gibbsite, compared with the more complex mineralogical composition of the actual waste solids. Despite these quantitative differences, both datasets indicate that incorporation of Al-rich solids promotes faster settling behavior than observed for the Fe-rich waste alone.

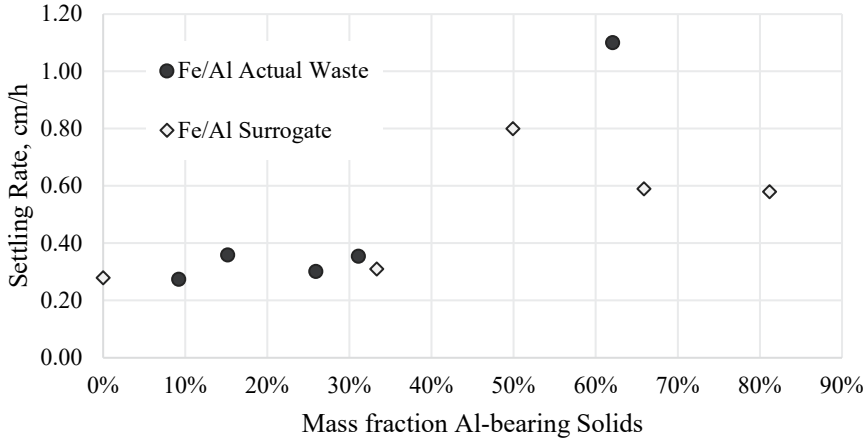


Figure 3.4 Settling rate as a function of Al-bearing solids fraction for surrogate and actual waste blends

3.4 Glass Former Addition Studies

Glass-forming chemicals were added to the PO_4-rich, U-rich, and actual Fe/Al blended waste slurries to evaluate the transport properties of candidate DFHLW melter feeds. Initial GFC additions were based on the oxide composition and projected waste loading for each slurry. The corresponding GFC-to-slurry ratios were 1.03 g/g for the PO_4-rich slurry, 0.90 g/g for the U-rich slurry, and 0.61 g/g for the Fe/Al blended slurry. These additions produced nominal post-GFC solids loadings of approximately 61, 58, and 50 wt%, respectively.

The as-blended GFC slurries exhibited substantially different glass yields due to differences in waste loading constraints and corresponding GFC requirements. The Fe/Al blended waste required the smallest quantity of GFCs and produced an as-blended glass yield of 919 g glass/L feed. In contrast, the U-rich and PO_4-rich wastes required significantly larger GFC additions, resulting in as-blended glass yields of 1195 and 1237 g glass/L feed, respectively. All three as-blended feeds exceeded the nominal target glass yield of 750 g glass/L feed. However, the magnitude of deionized water dilution required varied considerably among the waste types. A summary of the GFC dilution results is shown in Table 3-4.The

Fe/Al blended waste required only modest dilution, whereas the U-rich and PO_4-rich feeds required approximately 40% dilution to achieve the target glass yield. These results reflect the lower achievable waste loadings associated with the U-rich and PO_4-rich compositions and demonstrate that substantially greater water addition would be required to produce melter feeds within the desired operating window. All GFC slurries were then subsequently diluted further to target glass yields of approximately 620 and 500 g glass/L feed. All dilution targets were selected to bound the projected glass yield and density limits associated with melter feed preparation. Measured glass yields were generally close to the intended targets, although small deviations occurred because of material loss and practical limitations associated with hot-cell sample transfers.

Table 3-4 GFC Compositions and Dilution Summary

Sample	PO_4	U	Fe/Al
GFC:Slurry Ratio	1.03	0.9	0.61
As-Blended Density, g/mL	1.77	1.73	1.47
As-Blended Glass Yield, g/L	1237	1195	919
Dilution Required to Reach 750 g/L	39%	37%	18%
Dilution 1 Yield, g/L	763	767	744
Dilution 1 Density, g/mL	1.50	1.49	1.43
Dilution 2 Yield, g/L	622	629	639
Dilution 2 Density, g/mL	1.42	1.39	1.36
Dilution 3 Yield, g/L	509	521	532
Dilution 3 Density, g/mL	1.33	1.31	1.28

Settled bed shear strength measurements were performed on select GFC feeds to evaluate the potential for bed consolidation during storage and transport. Results are summarized in Table 3-5. The U-rich and PO_4-rich feeds exhibited relatively modest settled bed strengths, generally ranging from approximately 30 to 55 Pa regardless of glass yield or aging period. These measurements indicate that the settled solids remained relatively weak and readily mobilized during the specified storage durations. In contrast, the Fe/Al feed exhibited noticeably larger settled bed strengths, with measured values ranged from approximately 27 to 311 Pa. The elevated strengths are consistent with the higher fraction of Fe-bearing solids present in the Fe/Al blend and suggest a greater tendency toward formation of a cohesive settled solids structure following GFC addition.

Dilution generally reduced settled-bed strength for all waste types, however, the Fe/Al feed remained the most challenging material from a solids mobilization perspective even at the lowest glass yield evaluated. These results indicate that dilution alone may not fully mitigate settled-bed strength development in Fe-rich melter feeds. Aging time has relatively little effect on the U-rich and PO_4-rich feed, seen in Figure 3.5, whereas the Fe/Al feed exhibited substantial strength development during storage between 24 and 200 hours.

Table 3-5 Effect of Aging Time on Settled-Bed Shear Strength of GFC Slurries

Sample	Settled Solids from Glass Yield	Aging Time, Hours	Average Shear Strength, Pa	Notes
U-rich	750 g/L	70.8	52.1	Duplicate measurements averaged
	500 g/L	24.5	42.5	
	500 g/L	198.5	46.6	Minimal strength increase with aging
PO4-rich	750 g/L*	48.8	32.0	
	750 g/L*	93.8	46.1	Average of measurements from 16 and 28 mm depths
	500 g/L	21.6	43.4	
	500 g/L	47.3	34.4	Average of measurements from 16 and 28 mm depths
	500 g/L	192.5	41.5	Average of measurements from 32 and 39 mm depths
Fe/Al-rich	750 g/L	91.8	311.4	Strongest valid measurements observed
	500 g/L	25.3	27.4	
	500 g/L	46.5	92.1	
	500 g/L	191.9	125.4	Significant strength gain with aging

Initial measurements of 5251 Pa (U-rich) and 771 Pa (Fe/Al) were excluded from averaging because the vane was positioned at or near the slurry surface (0–3 mm depth), resulting in measurements not representative of the settled bed.
*PO4-rich sample was reprepared after the 750 g/L shear strength measurements due to large chunks found at the bottom of the sample container. Subsequent measurements at 500 g/L glass yield were on the reprepared sample.

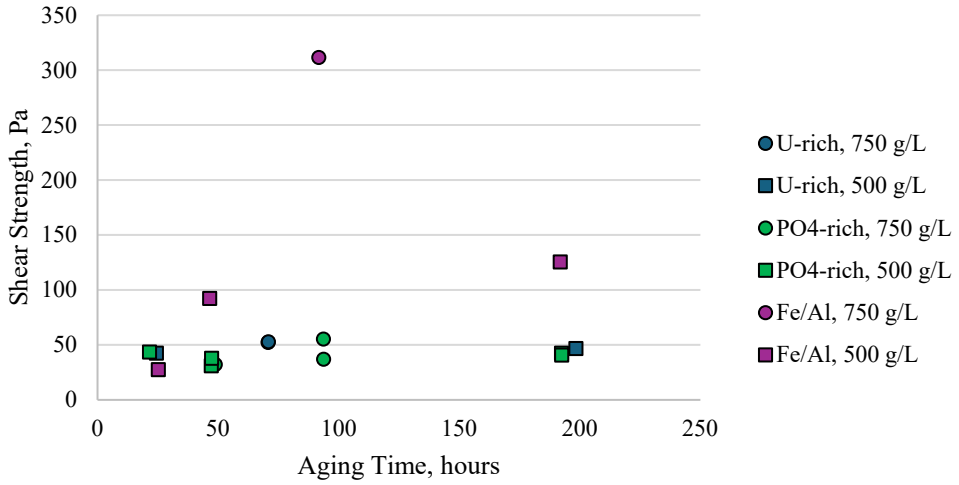


Figure 3.5 Shear strength development with aging for GFC Slurries

Table 3-6 Viscosity as a Function of GFC Slurries at 20 °C

Sample ID	Glass Yield	Wt% Solids	Yield Stress Pa	Viscosity Down Ramp, cP
U-rich	750 g/L	43.2	0.2	3.6
	625 g/L	39.9	0.1	3.3
	500 g/L	35.6	0	2.6
PO_4-rich	750 g/L	44.3	0.6	16
	625 g/L	40.6	0.5	6.6
	500 g/L	36.9	0.3	3.9
Al/Fe-rich	750 g/L	43.9	0.0	9.9
	625 g/L	39.3	0.0	5.6
	500 g/L	33.0	0.0	3.5

4.0 Conclusions

The work detailed in this report evaluated the effects of waste blending and GFC addition on the transport properties of representative Hanford DFHLW slurries using a combination of non-radioactive surrogate testing and confirmation experiments with actual waste composites. The results demonstrate that representative surrogate materials can be developed to reproduce the transport behavior of challenging waste systems and provide an effective means for evaluating blending strategies prior to consuming limited actual waste samples.

Development of the Fe-rich surrogate successfully reproduced the key transport characteristics of the actual Fe-rich waste composite. Incorporation of Fe_2O_3 into a precipitated Fe-rich hydroxide sludge produced a surrogate that closely matched the settled solids concentration, settled-bed shear strength, and just-suspended impeller speed (N_{JS}) measured for the actual waste.

Blending studies demonstrated that incorporation of Al-rich solids progressively improved the transport behavior of Fe-rich waste systems. Both the surrogate and actual waste blends exhibited increased settled solids concentrations with increasing Al-bearing solids content, indicating improved solids consolidation while maintaining settling behavior representative of Hanford waste slurries. More importantly, the actual Fe/Al blend at equal ratios Al-rich and Fe-rich slurry composites exhibited a 20% reduction in N_{JS} than the Fe-rich waste composite, demonstrating that blending with Al-rich waste reduced the impeller speed required to achieve complete solids suspension. These results confirm that blending can partially mitigate the elevated suspension requirements associated with Fe-rich waste while preserving the ability to suspend the slurry using practical mixing conditions.

The shear strength results further support the effectiveness of the blending strategy. The Fe/Al blended waste exhibited an average settled-bed shear strength of approximately 24 Pa, which remained comparable to the Fe-rich waste composite (21 Pa) and substantially lower than the Al-rich waste composite (57 Pa). These results indicate that blending significantly improved solids suspension behavior without producing the stronger settled beds associated with the Al-rich waste. Consequently, the blended waste maintained favorable remobilization characteristics while simultaneously reducing the mixing intensity required for solids suspension.

Glass-forming chemical additions substantially increased the solids inventory of all candidate melter feeds. The projected glass formulations produced as-blended glass yields ranging from approximately 919 g glass/L feed for the Fe/Al blended waste to greater than 1200 g glass/L feed for the U-rich and PO_4-rich wastes, requiring dilution to achieve target operating glass yields. These results demonstrate that projected waste loading has a significant influence on the physical properties of DFHLW melter feeds and highlight the importance of considering transport behavior alongside glass formulation requirements during process development.

Following GFC addition, the Fe/Al blended waste continued to exhibit the most challenging transport characteristics of the three waste systems evaluated. While the U-rich and PO_4-rich feeds exhibited relatively modest settled-bed shear strengths with little evidence of time-dependent strength development, the Fe/Al blended feed developed substantially greater settled-bed strengths during quiescent aging, indicating continued consolidation of the settled solids.

Overall, the results demonstrate that blending Fe-rich waste with Al-rich waste represents a promising strategy for improving slurry transport behavior prior to melter feed preparation. The combination of reduced N_{JS} requirements, maintenance of low settled-bed shear strength, and improved settling behavior indicates that blending can alleviate several of the transport challenges associated with Fe-rich waste without introducing the stronger settled beds characteristic of Al-rich waste. Furthermore, the close

agreement between surrogate and actual waste trends demonstrates that the non-radioactive surrogate methodology provides an effective tool for evaluating future blending strategies while minimizing consumption of limited radioactive waste inventory.

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