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CONSOLIDATION STRENGTH CHARACTERISTICS OF PYRITIC URANIUM TAILINGS USING: 1) POWDERED AND HYDRATED LIME IN A CARBON DIOXIDE ENVIRONMENT; 2) SLAG CEMENT

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ABSTRACT

In order to evaluate in situ consolidation and strength characteristics of pyritic tailings stabilized with lime and carbon dioxide, laboratory consolidation tests were carried out for tailings mixed with powdered lime, hydrated lime and blast furnace slag cement under carbon dioxide, nitrogen and air environments. The specimen samples were cured for 28 days at room temperature (22 ± 2^oC) and saturated moisture conditions (100% relative humidity) and their uniaxial compressive strengths and tangent modulii of elasticity measured. The compressive strengths varied from 250 to 325 kPa for powdered lime control, 260 to 342 kPa powdered lime - CO_2 mixing, 81 to 311 kPa for hydrated lime - control, 238 to 254 hydrated lime CO_2 mixing, and 5293 to 5697 kPa for the slag cement. The tangent modulii of elasticity were measured as, respectively, 37 to 54 kPa, 30 to 44 kPa, 1 to 3 kPa, 1.7 to 3.4 kPa, and 789 to 956 MPa for the above cases. For all samples, the compressive strengths were similar for both powdered and hydrated lime samples with no significant variations among various tailings and lime ratios. For both carbon dioxide and nitrogen mixing environments, the ultimate strengths were comparable to tailings/cement and tailings/lime stabilization results and no noticeable effect of CO_2 mixing was observed. For the case of hydrated lime control samples a decrease in compressive strength with increased lime content was observed as a result of excess retained moisture (21 to 29%) after curing. The highest compressive strength and modulus of elasticity were obtained for blast furnace slag cement where the presence of aluminum oxide and silica provided additional binding and strength with the formation of hydrated alumino silicates.

Key words: Tailings; Consolidation; Compressive strengths; Stabilization.

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DÉTERMINATION DES CARACTÉRISTIQUES DE RÉSISTANCE À LA CONSOLIDATION DES RÉSIDUS D'URANIUM PYRITEUX À L'AIDE DE:
1) CHAUX PULVÉRISÉE ET HYDRATÉE DANS UN MILIEU D'ANHYDRIDE CARBONIQUE;
2) CIMENT DE LAITIER

par

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RÉSUMÉ

Dans le but de déterminer les caractéristiques de consolidation et de résistance in situ des résidus pyriteux stabilisés avec de la chaux et de l'anhydride carbonique, les auteurs ont effectué des essais de consolidation en laboratoire avec des résidus mélangés à de la chaux pulvérisée, de la chaux hydratée et à du ciment de laitier de haut fourneau dans des milieux d'anhydride carbonique, d'azote et d'air. Les échantillons ont été conservés à la température ambiante (22 ± 2°C) pendant 28 jours dans des conditions d'humidité saturées (100 % d'humidité relative), et la résistance à la compression uniaxiale et les modules d'élasticité tangents de ces échantillons ont été mesurés par la suite. Les données obtenues pour les essais de résistance à la compression variaient de 250 à 325 kPa pour les essais avec la chaux pulvérisée, de 260 à 342 kPa pour le mélange de chaux pulvérisée et de CO_2, de 81 à 311 kPa pour les essais avec la chaux hydratée, de 238 à 254 kPa pour le mélange de chaux hydratée et de CO_2, et de 5 293 à 5 697 kPa pour le ciment de laitier. Les données du calcul des modules d'élasticité tangents ont été présentées comme étant 37 à 54 kPa, 30 à 44 kPa, 1 à 3 kPa, 1,7 à 3,4 kPa et de 789 à 956 MPa pour les cas susmentionnés respectivement.

Mots-clés: Résidus; Consolidation; Résistance à la compression; Stabilisation.

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Les données obtenues pour la résistance à la compression de tous les échantillons étaient semblables à la fois pour les échantillons de chaux pulvérisée et hydratée, sans aucune variation importante entre les différents taux de résidus et de chaux. Pour les deux mélanges d'anhydride carbonique et d'azote, les données de la résistance maximale étaient comparables aux résultats de la stabilisation résidus/ciment et résidus/chaux, et aucun effet remarquable du mélange de CO_2 n'a été observé. Dans le cas des échantillons expérimentaux de chaux hydratée, une baisse au niveau de la résistance à la compression a été observée lors de l'augmentation de la teneur en chaux en raison du surplus d'humité retenue (21 à 29 %) après la période de conservation. Les résultats du calcul de la résistance et du module d'élasticité les plus élevés ont été obtenus avec le ciment de laitier de haut fourneau, où la présence d'oxyde d'aluminium et de silice a donné des propriétés agglutinantes et une résistance additionnelles lors de la formation d'alumino silicates hydratés.

INTRODUCTION

The mining industry produces large amounts of mill waste in the form of solid residue or tailings which are usually deposited in extensive tailings impoundments located above grade, or in shallow depressions. During the operating phase of the mine, part of these tailings is used in backfill operations where cemented coarse cycloned tailings are poured into worked-out excavations to increase ground support, provide safe pillar recovery and to minimize the effects of surface subsidence caused by mining operations. Hydraulic backfill technology requires improved drainage characteristics of the fill material for rapid removal of water, and hence the utilization of only coarse tailings fractions. The bulk of tailings fines are still discharged to tailings impoundments where the solids are allowed to settle, and the excess water is decanted off.

After cessation of mining operations, or when the tailings area becomes inactive, a reclamation program is followed where the tailings surface is stabilized, usually by revegetation to control wind and water erosion. In many cases, minerals such as pyrite, pyrrhotite and trace amounts of other metal sulphides which are not recovered in the milling process are also discharged as tailings. Upon weathering, these sulphides oxidize producing highly acidic conditions within tailings with the subsequent leaching of other residual minerals. The tailings porewater in the upper strata is thus highly acidic and contains many dissolved metals and sulphates. With precipitation and recharge events, these oxidation reaction products leave the tailings area via surface run-off, and as sub-surface seepage to the surrounding water courses, thereby altering their natural water quality. To date, the tailings management technology requires that all water leaving a tailings area be collected and treated to meet the recommended environmental guidelines.

Long term management scenarios of such acid producing tailings require investigations into areas where the available oxygen and moisture required for oxidation and the subsequent mobilization of reaction products with infiltration can be drastically reduced. In situ consolidation of tailings with the injection of a slaked lime slurry followed by carbon dioxide for curing (1) is one possible approach which needs to be evaluated. The principal binding reaction in the above process is the formation of a hardened complex hydrated silicate and carbonate matrix.

It is known from backfill studies that both cement and lime stabilized tailings have suitable settling and strength characteristics for stabilization (2-5). The effect of carbon dioxide in further improving consolidation and strength was investigated in this study. Before a detailed field investigation can be undertaken, laboratory consolidation studies were carried out by mixing various proportions of unclassified pyritic uranium tailings and lime in carbon dioxide and nitrogen (for control) environments. Tests were also conducted for tailings mixed in air with different proportions of blast furnace slag cement. The final mixes were cured for 28 days in a 100% relative humidity environment (to simulate saturated field conditions) and engineering parameters such as uniaxial compressive strength and tangent modulus of elasticity were measured. These results were compared with those of tailings/cement and tailings/lime stabilization tests.

SAMPLE PREPARATION AND TESTING PROCEDURE

Unclassified pyritic uranium tailings from the uranium mill of Denison Mines Ltd, in Elliot Lake, Ontario, were used for these tests. The tailings were obtained from the belt filters after the leaching stage and consisted of a mixture of sand and silt (50% less than 150 μm) comprised mainly of quartz, feldspar, approximately 5 to 7% pyrite and minor sericite. The tailings were air dried and homogenized. The consolidation test material was divided into three batches. In the first batch approximately 5 kg of dry tailings were mixed with powdered dry lime (CaO) in the ratios of 5, 10, 20, 30 and 50 to 1 tailings to lime in a cement mixture, for about 15 min. After the mix was completely homogenized, an appropriate amount of distilled water was added to produce a final pulp density of approximately 75% solids. It was mixed again for an additional half hour in a carbon dioxide environment by maintaining a constant gas flow in the mixing chamber. For control purposes, three samples in the ratios of 5, 10 and 30 to 1 tailings to lime were mixed in a nitrogen environment. In the second batch, identical samples were prepared similar to the first one, but in this preparation the powdered lime was first hydrated alone with the required water in the cement mixer for about 15 min, followed by appropriate amounts of tailings and mixed for an additional half hour in carbon dioxide and nitrogen environments. As a sub-group of this preparation, additional samples were mixed in the ratios of 5, 10 and 30 to 1 tailings to lime, first in air for half an hour, and then mixed again for an additional half hour in a carbon dioxide environment. This was done to determine differences in carbon dioxide curing during and after initial mixing. In the third batch, three samples containing 5, 10 and 30 to 1 tailings to lime portions were air mixed using a vitrified slag cement obtained as a by-product from a steel blast furnace (Reiss Lime, Algoma Steel) containing approximately 30.3% CaO, 8.9% Al_2O_3, and 38.4% SiO_2 (6).

The final sample mixes were poured slowly into pre-waxed cardboard cylindrical moulds of dimensions 152 mm height and 76 mm diameter. During and after pouring the cylinders were tapped gently to ensure that all the trapped air was removed. These cylinders were allowed to stand for half an hour and then covered with plastic bags and placed for curing at room temperature (22 ± 2°C) in a sealed moisture controlled environment maintained at close to 100%

relative humidity. This was done to simulate a saturated zone tailings environment in the field.

After 28 days of curing, the cylinders were removed and separated from the cardboard holders. The edges were then cut and smoothed so as to ensure that the end surfaces were perpendicular to the cylindrical axis, as near as practically possible. The cylinders were placed in a vertical press and the uniaxial compressive strength along the cylindrical axis was measured. The tangent modulus of elasticity was also calculated from the observed stress/strain plots. After completion of the tests, the specimen samples were placed in paper bags, air dried at 105°C in an oven to a constant weight and the evaporable moisture content was determined. A screen analysis of the homogenized tailings was also performed.

RESULTS AND DISCUSSION

Figure 1 shows the grain size distribution of the sample tailings with D_{10} and D_{60} equal to 47 μm and 166 μm, respectively. Figures 2, 3 and 4 show typical load displacement curves obtained for the three different cases of powdered lime, hydrated lime and Reiss lime.

Tables 1, 2 and 3 show, respectively, the measured uniaxial compressive strength, σ_c, tangent modulus of elasticity, E, and the actual and evaporable moisture contents of various samples for the three different categories.

It can be seen from these results that for the three different examples, the highest uniaxial compressive strength, ranging from 5293 to 5697 kPa, and the highest tangent modulus of elasticity, ranging from 789 to 956 MPa, were obtained for Reiss lime (slag cement) stabilized tailings. In both powdered and hydrated lime stabilized samples the compressive strengths were comparable to carbon dioxide mixing, varying between 259 and 342 kPa for powdered lime, between 239 and 318 kPA for hydrated lime with CO_2 mixing, and between 296 and 354 kPa for hydrated lime with air followed by CO_2 mixing. The tangent modulii of elasticity were, however, one order of magnitude lower for the hydrated lime than for the powdered lime.

One striking difference between the two treatments is in their results for control samples where, for the powdered lime case, both the uniaxial compressive strengths and tangent modulus of elasticity were statistically indistinguishable from those of CO_2 mixing (Table 1). For the hydrated lime, on the other hand, their value decreased with the increase in the lime content (Table 2). These latter results are in significant contrast to results reported by Weaver and Luka (2) for cement stabilized tailings, and by Arïoglu et al. (5) for lime stabilized tailings, where the strength increased with the amount of lime content. In the present case, no such results were observed for the different categories where the strength characteristics remained virtually unchanged as the lime contents were increased. This was probably caused by the high total moisture content of the samples (Tables 1 to 3) resulting from curing at saturated moisture conditions.

For the hydrated lime control samples, evaporable moisture content increased from 21 to 29% as the lime to tailings ratio increased from 0.033:1 to 0.2:1, which resulted in a decrease in strength from 311 kPa to 81 kPa and tangent modulus of elasticity from 1.9 to 1.0. For the powdered lime control samples the evaporable moisture remained practically constant, resulting in similar compressive strengths and tangent modulii of elasticity. It is well known for the case of concrete and plaster that the compressive strength decreases with the increase in water/cement or plaster ratio (5) and with porosity. Though the amount of water added to the present samples was based on calculations requiring complete hydration of lime and wetting of mixed components, the results showed incomplete hydration giving rise to higher free water and thus decreased strength. A core analysis of the test samples revealed clusters of poorly hydrated lime particles in most cases.

Though the ultimate strengths for powdered and hydrated lime stabilized tailings were similar to values reported in the literature for other stabilization techniques (2,5), no effect of carbon dioxide mixing and curing was observed. At the time of mixing it was seen that although carbon dioxide environments resulted in initial clumping and rapid consolidation of the tailings mass, it gradually sheared with increased mixing to a uniform consistency similar to those without carbon dioxide. Carbonate mineralization was present in the specimen samples, but no additional advantage in the strength was observed. Initial hydration of lime prior to its mixing with tailings resulted in different elastic characteristics (Figures 1 and 2) where the tangent modulus of elasticity decreased by a factor of about 20 compared to that for the powdered lime samples. No significant differences were observed between CO_2 and air followed by CO_2 mixing.

The presence of aluminum oxide and silica in Reiss lime provided additional binding and strength with the formation of hydrated alumino silicates resulting in much higher compressive strength and modulus of elasticity, similar to other aluminous cements.

CONCLUSIONS

From this investigation, it can be concluded that:

1. For both powdered and hydrated lime stabilized tailings, the compressive strengths were similar to other stabilization techniques.
2. No effect of carbon dioxide mixing was observed on the ultimate strength characteristics.
3. Because of higher evaporable moisture contents, no additional gain in strength was observed with increased lime content.
4. The highest strength and modulus of elasticity were obtained for Reiss

lime (slag cement) because of the additional binding and strength resulting from the hydration of alumino silicates.

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Table 1 - Uniaxial compressive strength, tangent modulus of elasticity, actual and evaporable moisture content for tailings and powdered lime stabilized samples.

Sample ID	Tailings:Lime Ratio	Uniaxial Compressive Strength σ_c, (kPa)	Tangent Modulus of Elasticity, E (MPa)	Actual Moisture Content at Mixing (%)	Evaporable Moisture Content After Test (%)
Control	30:1	250 ± 61	37.8 ± 37.8	27.8	20.4 ± 1.1
Control	10:1	325 ± 34	54.5 ± 9.1	25.7	20.3 ± 0.7
Control	5:1	292 ± 15	37.1 ± 13.3	31.4	21.9 ± 0.6
CO_2 mixing	50:1	259 ± 69	43.6 ± 3.9	26.3	20.3 ± 0.8
CO_2 mixing	30:1	338 ± 50	42.2 ± 12.3	26.5	19.1 ± 0.7
CO_2 mixing	20:1	260 ± 61	37.1 ± 19.6	27.3	19.6 ± 0.3
CO_2 mixing	10:1	342 ± 30	29.6 ± 4.7	25.7	18.1 ± 1.0
CO_2 mixing	5:1	276 ± 42	38.4 ± 44.0	31.4	19.3 ± 0.7

Table 2 - Uniaxial compressive strength, tangent modulus of elasticity, and actual evaporable moisture content for tailings and hydrated lime stabilized samples.

Sample ID	Tailings:Lime Ratio	Uniaxial Compressive Strength σ_c, (kPa)	Tangent Modulus of Elasticity, E (MPa)	Actual Moisture Content at Mixing (%)	Evaporable Moisture Content After Test (%)
Control	30:1	311 ± 23	2.9 ± 0.5	27.8	20.9 ± 0.4
Control	10:1	129 ± 6	1.2 ± 0.2	25.7	24.9 ± 0.2
Control	5:1	81 ± 5	1.0 ± 0.3	31.4	28.9 ± 2.7
CO_2 mixing	50:1	239 ± 32	1.7 ± 0.4	26.3	20.7 ± 1.1
CO_2 mixing	30:1	243 ± 14	1.8 ± 0.1	26.5	21.5 ± 0.4
CO_2 mixing	20:1	249 ± 11	1.9 ± 0.1	27.3	21.1 ± 1.5
CO_2 mixing	10:1	238 ± 41	1.8 ± 0.3	28.5	20.3 ± 0.1
CO_2 mixing	5:1	319 ± 147	1.8 ± 0.3	31.4	23.1 ± 1.1
Air followed by CO_2 mixing	30:1	354 ± 41	3.4 ± 0.5	24.6	17.9 ± 0.8
Air followed by CO_2 mixing	10:1	336 ± 20	3.1 ± 0.3	27.6	18.7 ± 0.2
Air followed by CO_2 mixing	5:1	296 ± 18	2.5 ± 0.1	28.9	19.9 ± 0.2

Table 3 - Uniaxial compressive strength, tangent modulus of elasticity, and actual evaporable moisture content for tailings and Reiss Lime (slag cement) stabilized samples.

Sample ID	Tailings:Lime Ratio	Uniaxial Compressive Strength σ_c, (kPa)	Tangent Modulus of Elasticity, E (MPa)	Actual Moisture Content at Mixing (%)	Evaporable Moisture Content After Test (%)
Reiss Lime	30:1	5697 ± 331	933 ± 159	22.9	11.8 ± 4.0
Reiss Lime	10:1	5293 ± 848	956 ± 441	22.8	14.4 ± 4.5
Reiss Lime	5:1	5679 ± 544	789 ± 114	20.9	17.3 ± 0.1

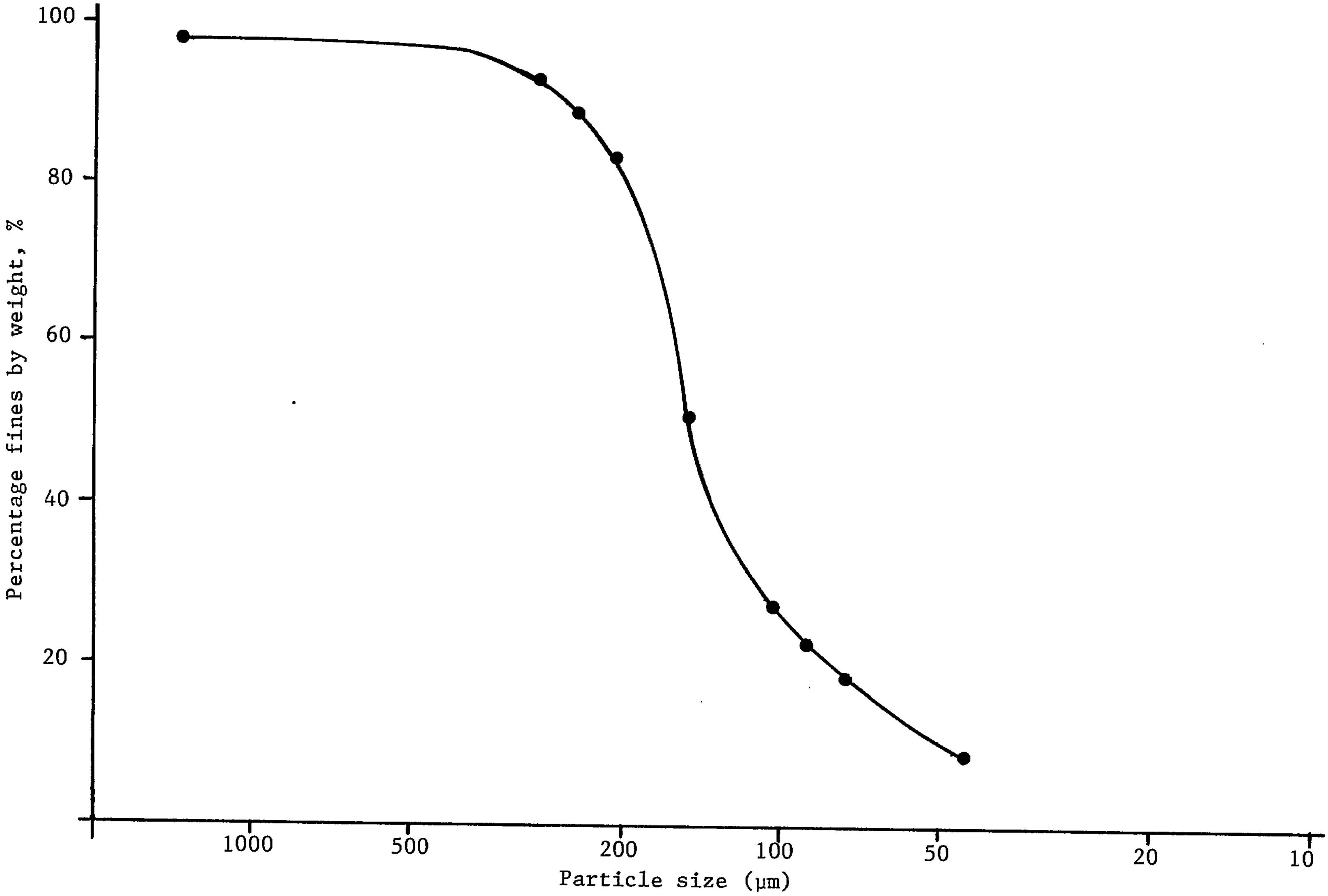

Fig. 1 - Grain size distribution of sample uranium tailings.

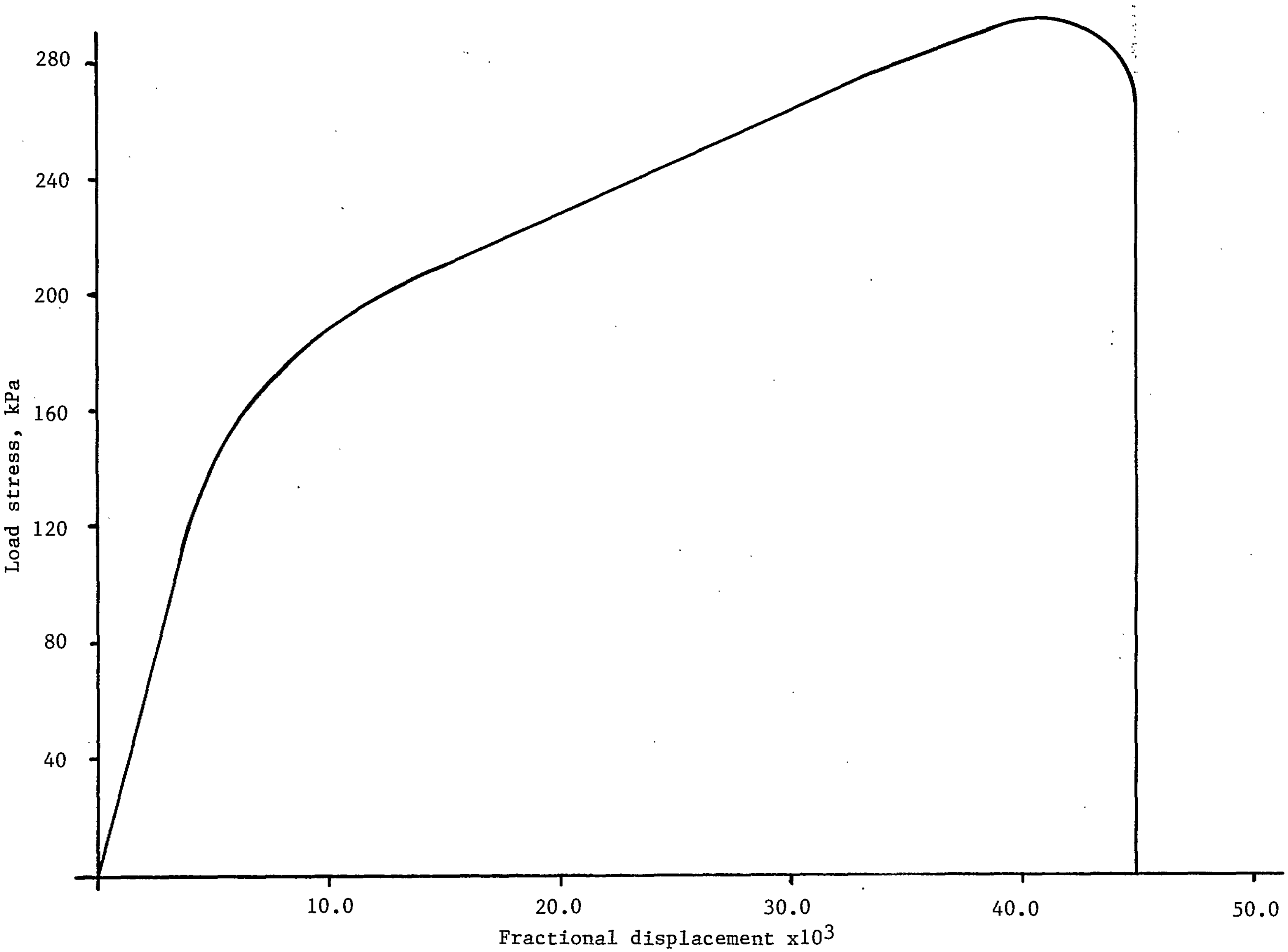

Fig. 2 - Load-displacement and failure curve for a typical powdered lime stabilized sample.

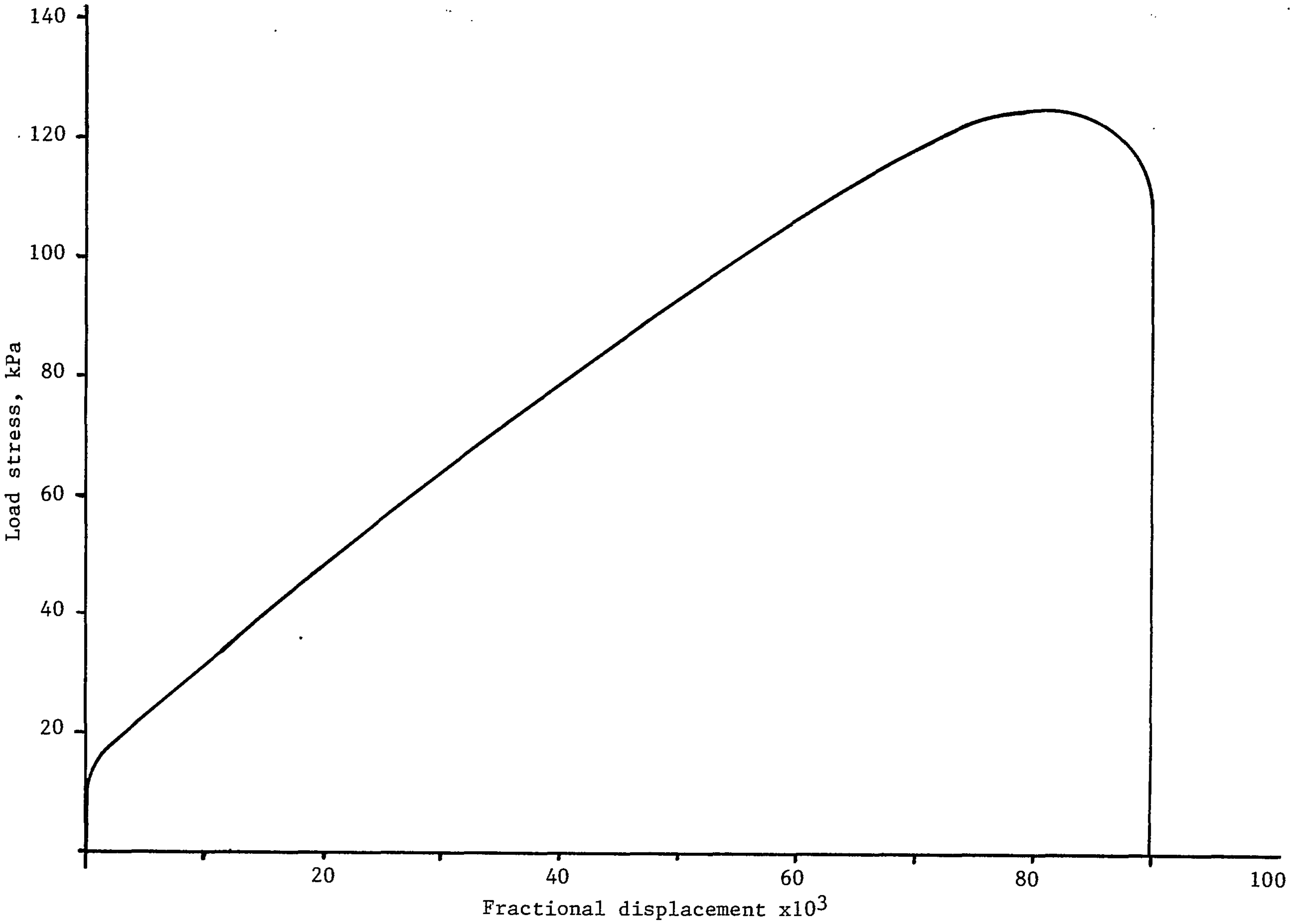

Fig. 3 - Load-displacement and failure curve for a typical hydrated lime stabilized control sample.

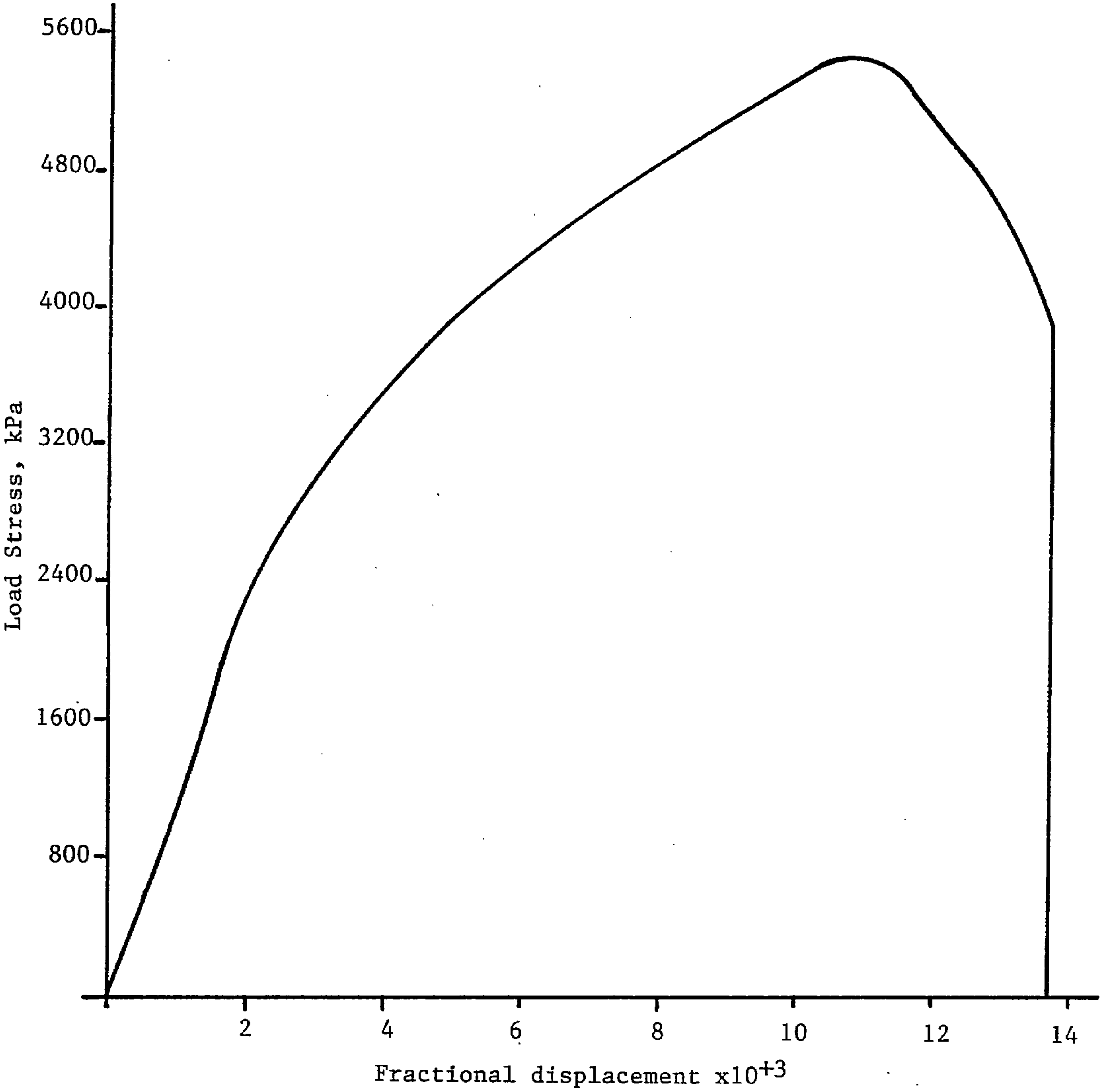

Fig. 4 - Load-displacement and failure curve for a typical Reiss lime (slag cement) stabilized sample.