Extended Abstract

This study investigates the air flow in the unsaturated zone induced by vapor extraction with carbon monoxide as a tracer gas. Soil vapor extraction is a method for the in situ removal of volatile contaminants from the unsaturated zone by either removing the vapor phase contaminants through the air spaces in the soil or by transferring contaminants from residual liquid and dissolving phases to the vapor phase. In all cases, knowledge of the radius of influence and flux of soil gas is important to improve the amount of contaminants which are removed from the soil. Tracer experiments are useful to understand the flow of the soil gas and to estimate the air-permeability in the homogenous or heterogeneous unsaturated zone. In this investigation field experiments as well as laboratory experiments were carried out to show the suitability of carbon monoxide as a tracer for the unsaturated zone.

To ensure successful use of a tracer experiment, a tracer must show certain qualities, e.g., easy detection and limited natural concentration in the soil air. The natural occurrence of carbon monoxide in the underground at every field experiment was less than the measurement equipment could detect (< 2ppm). To get good breakthrough curves only small amounts of carbon monoxide were necessary and the concentrations used in field as well as in laboratory experiments were not dangerous for human beings or animals. The continuous recording of the carbon monoxide concentration was performed with a portable gas measurement instrument which was connected to a portable computer. The chemical properties of air and carbon monoxide, e.g. the density, are similar and therefore the movement of both gases in the underground should be the same. The simultaneous use of carbon monoxide and carbon dioxide as tracers demonstrated that the influence of different densities of both gases is negligible within the time of a tracer experiment. The solubility of carbon monoxide and carbon dioxide in soil water can cause a lower recovery rate. Laboratory experiments with both gases at increasing water contents, however, showed no decrease of the recovery rates and therefore the solubility in soil water can be ignored during the short time of a tracer experiment. Adsorption tests with clay minerals at different water contents showed decreasing amounts of adsorbed carbon monoxide with increasing adsorption of water on a clay mineral. The amount of carbon monoxide that can be adsorbed on clay minerals is negligible in natural conditions.

In both laboratory and field experiments the air permeability was calculated with DARCY's Law. The exact flow and pressure conditions were determined to prove the applicability of DARCY's law for tracer experiments in the unsaturated zone. The breakthrough curves of the tracer experiments were analyzed with different methods, where the best results were achieved with the best-fit method based on the evaluation from LENDA & ZUBER (1970).

In laboratory experiments the influence of water content and bulk density on the air permeability of sand were examined in a test column. The tracer experiments showed significant increase of the air permeability at higher pore volumes but the influence of increasing water content up to 10 - 12 % by weight was not significant. Soil water is located in smaller pores at low water contents and did not noticeably affect the air flow through the unsaturated zone, therefore, the air permeability was not decreased significantly. At higher water contents (12 - 15% by weight) the larger pores were also filled which caused a decrease in the air permeability. The calculated recovery rates did not depend on the air flow through the system nor on the injected amount of tracer. Higher recovery rates were achieved by reconstructing the test column.

Combined tracer experiments were performed in order to compare carbon monoxide and carbon dioxide as tracers. The injected amount of carbon dioxide was calculated by using the pressure vessel filled with carbon dioxide. From earlier experiments, small amounts (< 0,5 %) of carbon monoxide remained in the vessel and caused an additional breakthrough curve. A significant breakthrough curve was measured in spite of the low concentration of carbon monoxide in the vessel. The small amount of carbon monoxide needed for the laboratory experiment was therefore injected with a syringe and the vessel, where the injection pressure causes earlier travel times, was not required.

Carbon monoxide is used as a tracer gas in three field experiments to determine the influence of the sealed surface and the flow of air through artificial channel systems or to determine the area through which most of the soil air is streaming to the venting system. For the subterranean injection of carbon monoxide, either injection wells on selected test areas were installed surrounding the venting system or existing extraction wells were used as injection wells. During the vapor extraction, the distribution of the underground

pressure was recorded with digital pressure detectors. The radius of influence of the soil vapor extraction system and the flow through the unsaturated zone was estimated from these results. A disturbance of air flow in the underground based on a layer of clay or the mutual influence of several venting systems can be located based on these tests. With knowledge of the underground pressure distribution a defined amount of carbon monoxide was injected with a pressure vessel. The temporal distribution of the carbon monoxide concentration was recorded behind the venting system. The tracer recovery was calculated to show the unity of the underground streaming system. Different velocities of the gas in the underground could be estimated from the evaluation of the breakthrough curves. The average coefficient of air-permeability of the unsaturated zone was derived using the mean velocity, the effective porosity for air, and the pneumatic gradient.

In the first experiment, the equipment to run tracer experiments was tested with the cleanup of the gravel underground from a gas station. The depth of the unsaturated zone was about 8.5 m. There was a 9 m deep excavation in the northern part of the contamination site where the contaminated soil was removed. In an existing soil venting system with one central extraction well, carbon monoxide was injected in four wells using different distances from the extraction well. Both the tracer experiments and the recording of the pressure distribution showed the influence of the excavation in the northern part of the contamination site. With these tests, the shape and the extension of the influence of the soil venting system could be estimated. In additional laboratory experiments comparable air permeability could not be achieved, however, due to the differences between natural deposition in the field and artificial layering in the test column.

In the second experiment carbon monoxide is used as a tracer to plan the position of a vapor extraction system. In the underground of a paint shop, halogenated hydrocarbons were discovered in a soil with low air conductivity. Based on the tracer examination on the first extraction well, the location of the second was suggested to achieve a maximum radius of influence. The results of the tracer experiments indicated a higher air conductivity through preferred flow paths, e.g. from the injection well through the fillup to the extraction well, where the filling was not done properly. In additional experiments with carbon monoxide as a tracer gas carbon dioxide was used to prove the comparability of both tracers. The amount of carbon dioxide used to produce a good breakthrough curve and to get the same results was much higher when compared with the amount of carbon monoxide. In order to keep the injection time as short as possible, the injection pressure had to be increased to get the carbon dioxide in the underground. The carbon dioxide tracer was faster than carbon monoxide due to the higher pressure in the test. In laboratory experiments the test column was filled with disturbed material from the site. In spite of the same bulk density the air permeability was too high for silt material. As a result of the accumulation of the soil during the build-in, artificial air channels were produced and the air permeability increased.

The application of carbon monoxide as a tracer on an existing soil venting system with several extraction wells is described in the third field experiment. In this experiment, the ground was contaminated with Phenols, PAK and halogenated hydrocarbons. Gravel and sand built up an unsaturated zone where the water table was about 35 m deep. The radius of influence of the extraction wells was recorded with pressure detectors. From the results of the pressure measuring tests an average radius of influence of 40 m could be estimated. Due to the high number of extraction wells, an overlap of the single venting systems was proven. Tracer experiments were used to determine the subsurface areas through which the soil air streams. Based on the results of these experiments the effect of the unsealed surface on the streaming system in certain areas could be demonstrated and a different removal technique was proposed to increase the amount of contaminants removed from the soil.

Field experiments with carbon monoxide as a tracer give evidence of the air flow and the air velocity in the underground. Using these results the soil venting systems were optimized and increased amounts of contaminants were removed. Due to its' low cost and easy detection, carbon monoxide is an ideal gas to trace the movement of soil air.