## 11.7 Relative permeabilities

Previously, we defined the permeability k as *the ability of a rock formation to conduct fluids*. Permeability is measured using a single fluid filling the pore space (remember Darcy's law). In practice, not one, but at least two or three fluids are present in the reservoir (water+oil, or water+oil+gas). The presence of other fluids will certainly affect the ability of a fluid to flow as you know from previous sections in this chapter.

Suppose two fluids are present, oil and water. The permeability of the rock to water when both oil and water are present will likely be lower than the permeability if water is the only fluid: Water now only occupies part of the pore space, and it will also be affected by interaction with the oil. Let's look at steady flow through a homogeneous horizontal core. In the pure water case, Darcy's law gives

$$q_w = -\frac{kA}{\mu_w}\frac{dp}{dx},$$

where k is the rock permeability.
When both oil and fluid are present, we would expect to find that

$$q_o = -\frac{k_o A}{\mu_o}\frac{dp}{dx},$$
$$q_w = -\frac{k_w A}{\mu_w}\frac{dp}{dx}.$$

Here, $k_o$ and $k_w$ are the *effective permeabilities* to oil and water respectively in the presence of the other fluid. It is common to write

$$k_o = k_{ro}k,$$
$$k_w = k_{rw}k,$$

where $k_{ro}$ and $k_{rw}$ are the *relative permeabilities* of oil and water respectively. Instead of the rock permeability k, any other *base permeability* may be used.

*What would the relative permeabilities depend on?*

*What assumption are we making in writing down the two equations for qo and qw?*

**Effect of saturation on relative permeability**

One of the main factors effecting relative permeability is, of course, saturation. Figure 11-17a displays a typical relative permeability curve for a two-phase system (wetting and non-wetting fluid) as function of the saturation $S_w$ of the wetting fluid. This figure was derived from an oil-water experiment in a water-wet rock. The relative permeabilities are here all given relative to the base relative permeability of oil at the irreducible water saturation $S_{wi}$ (also called the threshold water saturation).

Figure 11-17b shows the experiment, a water flood that was performed to get these data. At the beginning of the experiment the water-wet rock was saturated with 100% water. Then, oil is forced in to its maximum saturation of 100-$S_{wi}$ (here $S_{wi}$ is 20%). Point A represents the relative permeability in this situation. It is set equal to unity, because this is taken as the base permeability for this experiment. Point B represents the beginning water permeability. This is zero as expected as at $S_{wi}$ the water is not connected and can therefore not flow. Water is now injected into the core at one end. The volume of the fluids coming out at the other end is measured. The pressure difference over the core is measured as well. Over the course of this experiment, the permeability to oil reduces to zero along the curve ACD, and the permeability to water increases over the curve BCE. Note that there is no further production of oil from the sample after point D, which is the point of irreducible oil saturation.

*Why is* $k_{ro} + k_{rw} \leq 1$ *always?*

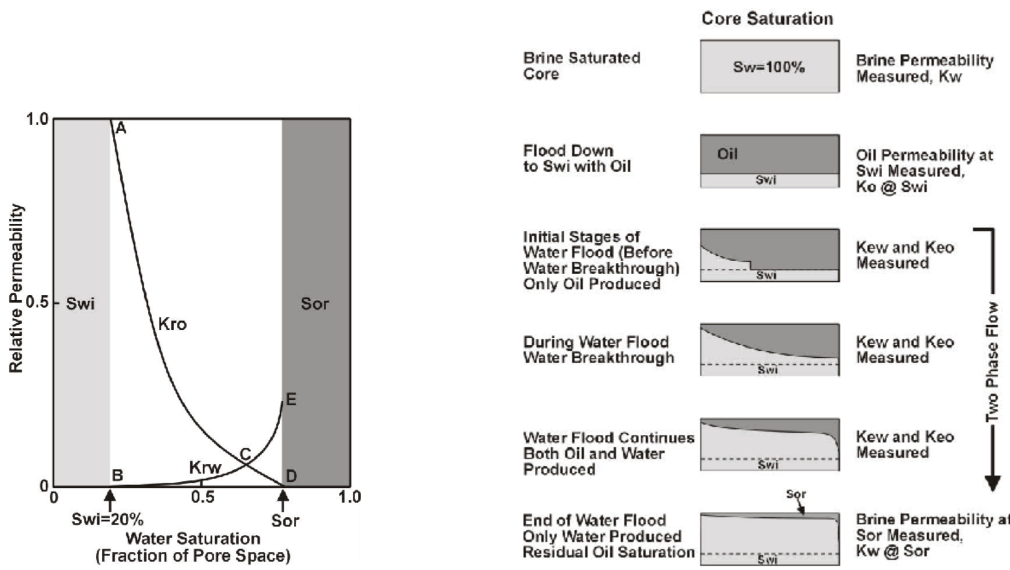


*Fig 11-17 a: typical relative permeability curve; b: water flood relative permeability measurement. Note that in this figure* $k_{ew}$ *and* $k_{eo}$ *are the effective permeabilities of water and oil respectively.*

**Other factors on which relative permeability depends**

*How can you tell from the relative permeability curve shown in figure 11-17a that water is the wetting fluid in this rock?*

From this question you can see that the relative permeability also depends on the wetting characteristics.

There are many more factors. We summarize them all here:

Factors affecting relative permeability are

- Saturation (and saturation history)
- Wetting
- Rock type (pore size distribution and pore configuration)
- Consolidation
- Viscosity ratio of the fluids present (but this effect is not great)
- Overburden pressure (again, effect is not great)

The wettability of the fluids determine the fluid distribution within the rock. If the rock is water wet, then at the threshold saturation for water, the relative permeability of the oil is very high and often close to 1, even though the rock is not fully saturated with oil. The water however sits in the small pores and they are not very important for fluid flow in the rock. On the other hand, immobile oil will sit in the larger pores and will therefore effect the relative permeability of water a lot. Therefore, the relative permeability at maximum water saturation is much smaller than 1.

*In the figure below, relatively permeability curves are sketched for unconsolidated material. What would the curves look like for consolidated material?*

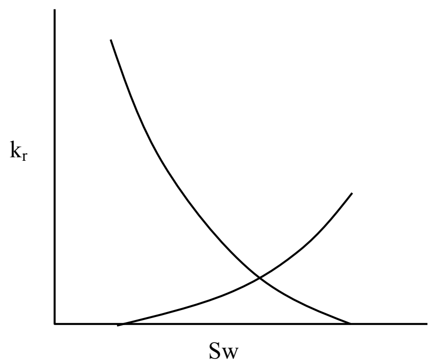


*Fig 11-18 Solid line: unconsolidated*