Scaling and saturation laws for the expansion of concrete exposed to sulfate attack

P. J. M., Monteiro, PNAS 2006 103: 11467-11472.
P.J.M. Monteiro and K.E. Kurtis, Experimental asymptotic analysis of expansion of concrete exposed to sulfate attack, ACI Materials Journal, Volume: 105, 62-71, 2008.

Experimental data

- The analysis will used the experimental results from the U.S. Bureau of Reclamation research on sulfate resistance of concrete.

- Concrete cylinders measuring 76-by-152mm were cast.

- The cylinders were fog cured for 14 days at 23 C, followed by 14 days drying at 50% RH at 23 C. At 28 days, the specimens were measured and then placed in a tank containing 2.1% (0.15M) Na_2SO_4 solution for 24 hours

Experimental data

- During the first 5 years of testing, measurements were made approximately every 28-30 days. After that, the cylinders were measured twice a year.
- After 20 years, the measurements were made annually.
- The sulfate solution was replaced as needed to maintain submersion of the cylinders, ensuring to some extent that sulfate ions remained in the surrounding solution over time.

Experimental data

- According to the USBR test method, a strain of 0.5% or greater indicated failure, and failed cylinders were removed from the sulfate solution, otherwise, measurements continued uninterrupted until 1991 – a test period of over 40 years.

- Data-set to study the effect of water-to-cement ratio

Sample	w/c	C_3A, %	C_3S, %	C_2S, %	C_4AF, %
5012	0.67	7	32	42	13
5014	0.67	7	32	42	13
5015	0.62	7	32	42	13
5016	0.62	7	32	42	13
5018	0.57	7	32	42	13
5019	0.57	7	32	42	13
5021	0.47	7	32	42	13
5023	0.47	7	32	42	13
5024	0.42	7	32	42	13
5026	0.42	7	32	42	13
7031	0.60	4	37	40	13
7032	0.60	4	37	40	13
7033	0.51	4	37	40	13
7034	0.51	4	37	40	13
7036	0.44	4	37	40	13
7038	0.44	4	37	40	13
7040	0.40	4	37	40	13
7041	0.40	4	37	40	13

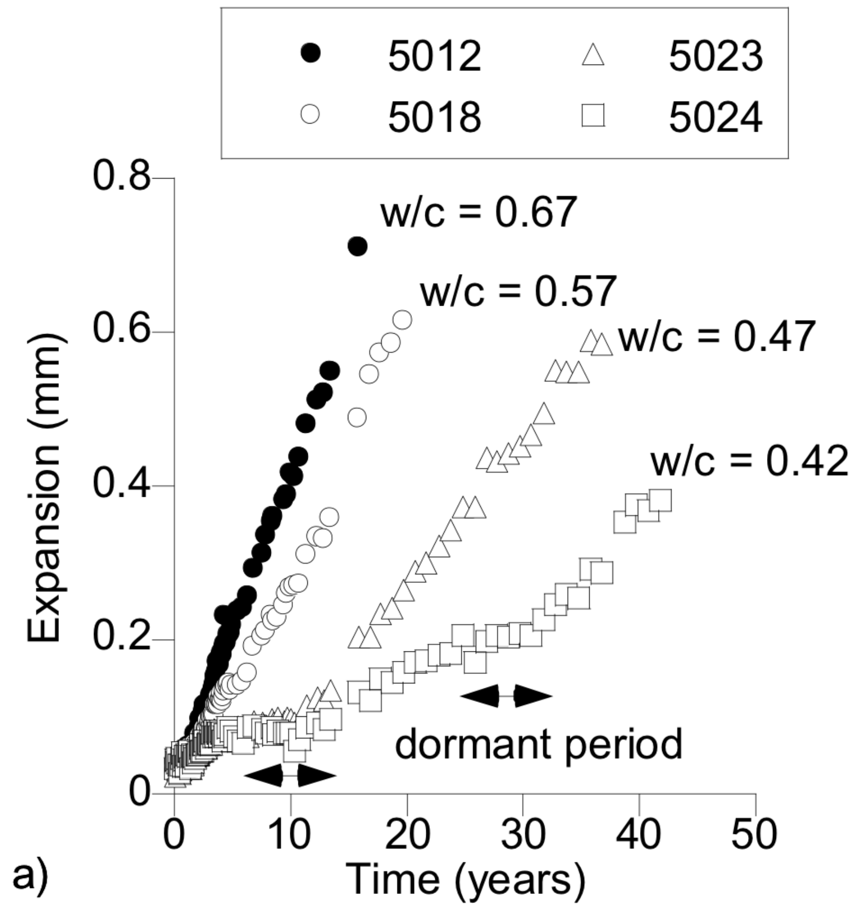
w/c, water-to-cement ratio.

Observations:

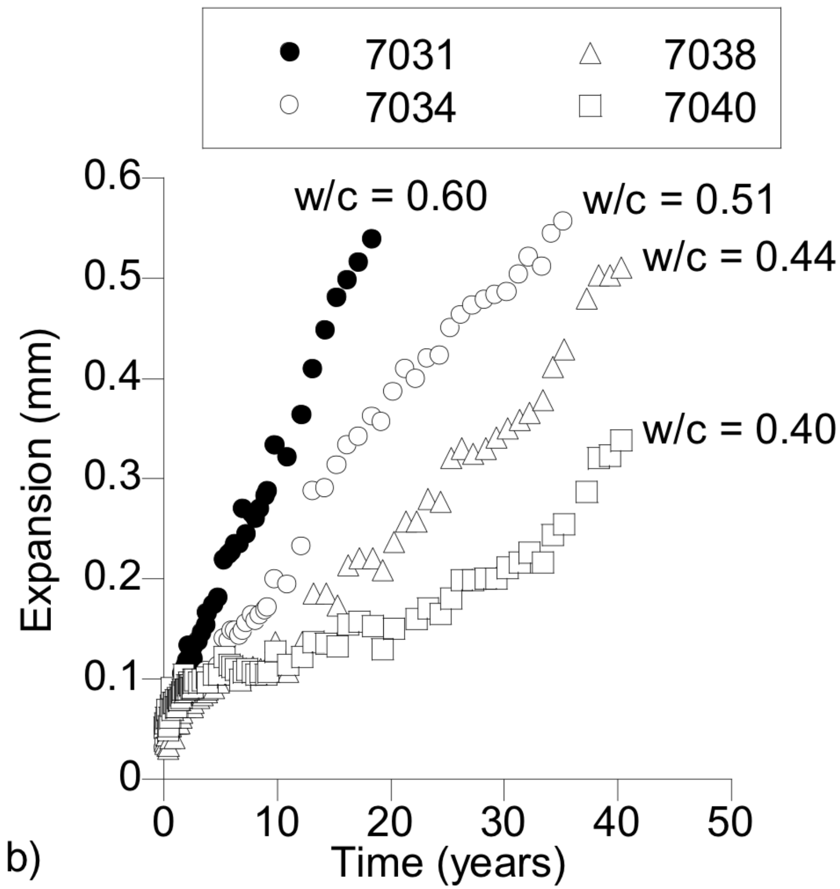
Samples 5012-5026 were cast with different water-to-cement ratios (0.67, 0.62, 0.57, 0.47, 0.42) and a constant cement composition;

Samples 7031-7041 were prepared with a wide range of water-to-cement ratios (0.60, 0.51, 0.44, and 0.40) and used a different cement compared to samples 5012-5026.

- Effect of water-to-cement ratio (w/c) on the expansion of concrete exposed to sulfate solution: cement 1



- Effect of water-to-cement ratio (w/c) on the expansion of concrete exposed to sulfate solution: cement 2



Discussion

- The water-to-cement ratio controls the porosity of the cement paste matrix.
- Concrete samples made with low water-to-cement ratio show an interesting “dormant period,” which can last up to 15 years.
- Besides the porosity of concrete, the chemistry of the cement also plays an important role in the development of the “dormant” period.

- The scaling law for the expansion of concrete exposed to sulfate attack can be expressed as:

$$\Delta L = K\left(t - t_o\right)^{\alpha}$$

where t_o is the effective origin of time, and a is the scaling exponent. *K* represents the specimen coefficient term that includes material properties and geometrical aspects of the sample.

Development of self-similar behavior for concrete samples

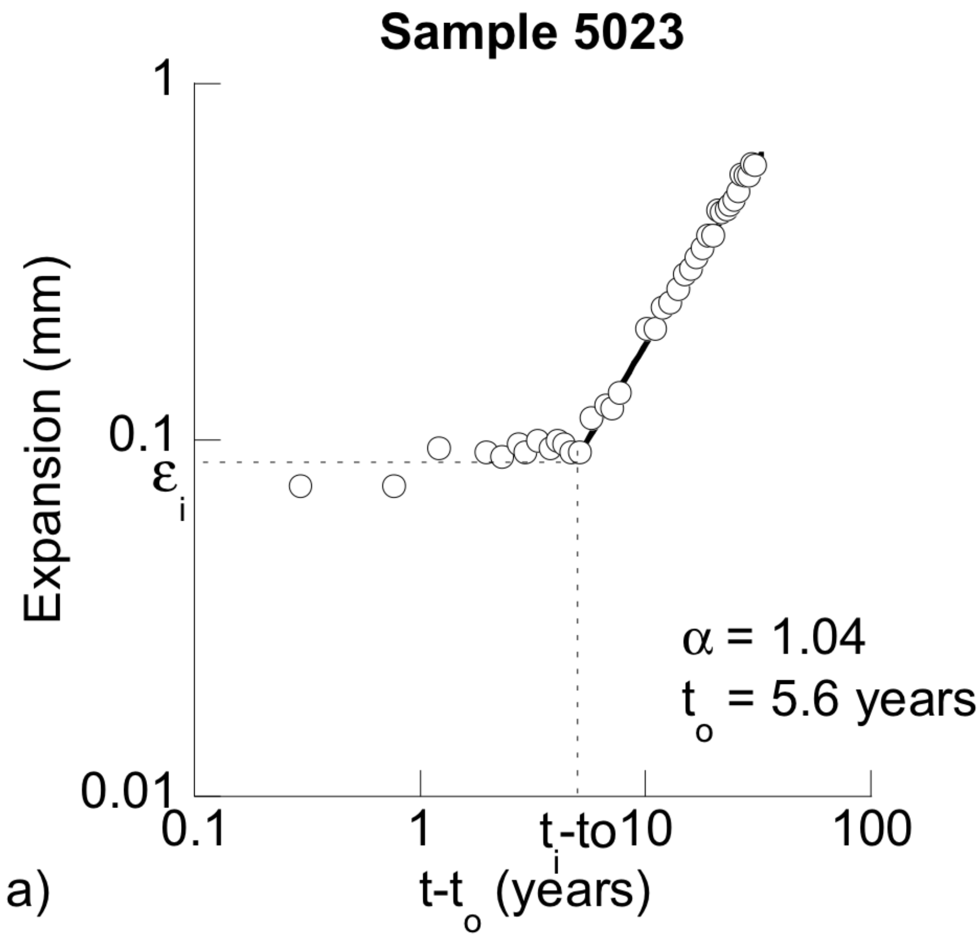


Table 1. Summary of the experimental results (effect of water-to-cement ratio)

Sample	w/c	C_3A, %	C_3S, %	C_2S, %	C_4AF, %	α	t_o, years	t_i, years
5012	0.67	7	32	42	13	1.11	−0.52	0.79
5014	0.67	7	32	42	13	1.15	−0.53	0.73
5015	0.62	7	32	42	13	1.18	−0.68	1.3
5016	0.62	7	32	42	13	1.19	−0.31	1.1
5018	0.57	7	32	42	13	1.01	0.00	2.15
5019	0.57	7	32	42	13	1.09	−0.12	2.15
5021	0.47	7	32	42	13	1.04	2.30	10.3
5023	0.47	7	32	42	13	1.04	5.60	10.1
5024	0.42	7	32	42	13		Saturation	
5026	0.42	7	32	42	13		Saturation	
7031	0.60	4	37	40	13	0.63	0.29	1.07
7032	0.60	4	37	40	13	0.73	0.15	1.32
7033	0.51	4	37	40	13	0.72	0.37	4.05
7034	0.51	4	37	40	13	0.71	1.58	4.02
7036	0.44	4	37	40	13		Saturation	
7038	0.44	4	37	40	13		Saturation	
7040	0.40	4	37	40	13		Saturation	
7041	0.40	4	37	40	13		Saturation	

w/c, water-to-cement ratio.

Observations

- Had the value of a been constant and equal to 0.5, one could infer that the dominant mechanism was the diffusion of the sulfate ions, however, the values of a were around 1.2 and 0.67 for cements 1 and 2, respectively.

Observations

- Note that for a given cement, alpha does not depend on the original water-to-cement ratio.
- Reducing the water-to-cement ratio has a significant effect on the initiation time.

Observations

- The reason why the scaling exponent alpha, which characterizes the intermediate asympotics stage, does not depend on the water-to-cement ratio is because during this stage a process of filtration develops in which the presence of fissures and percolation overwhelms the original differences of porosity in the matrix.

Observations

- Unlike the early initiation of the intermediate asymptotics for concrete samples made with high water-to-cement ratio, it takes many years for the intermediate asymptotics stage to begin when concrete mixes with lower water-to-cement ratios are used.

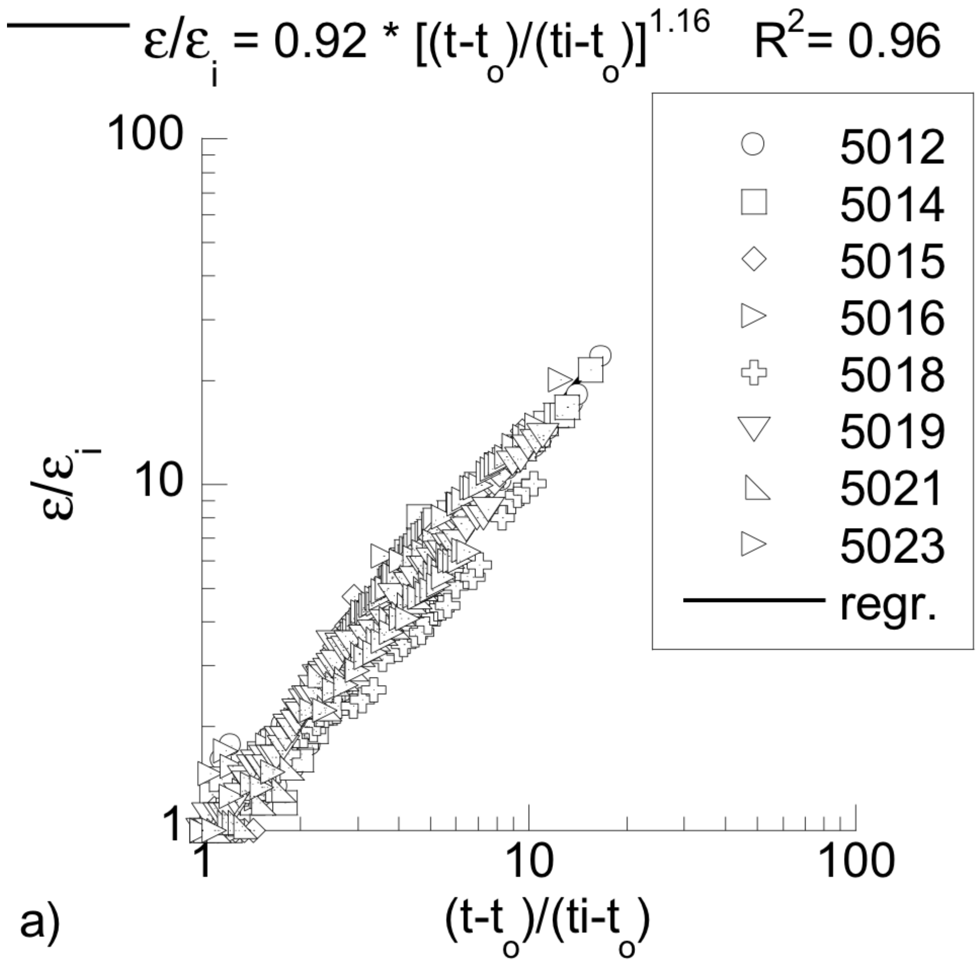
Observations

- It is possible to decouple the initial porosity controlled by the water-to-cement ratio in concrete to the type of cement.

Normalization

It is insightful to normalize the expansion ε and time $(t - t_o)$ to the expansion ε_i and the time $(t_i - t_o)$ of the beginning of the filtration process, respectively.

Next figure shows that using the new coordinate system, $\varepsilon/\varepsilon_i$ and $(t - t_o)/(t_i - t_o)$, all the expansion results for a given type of cement collapse into a straight line.



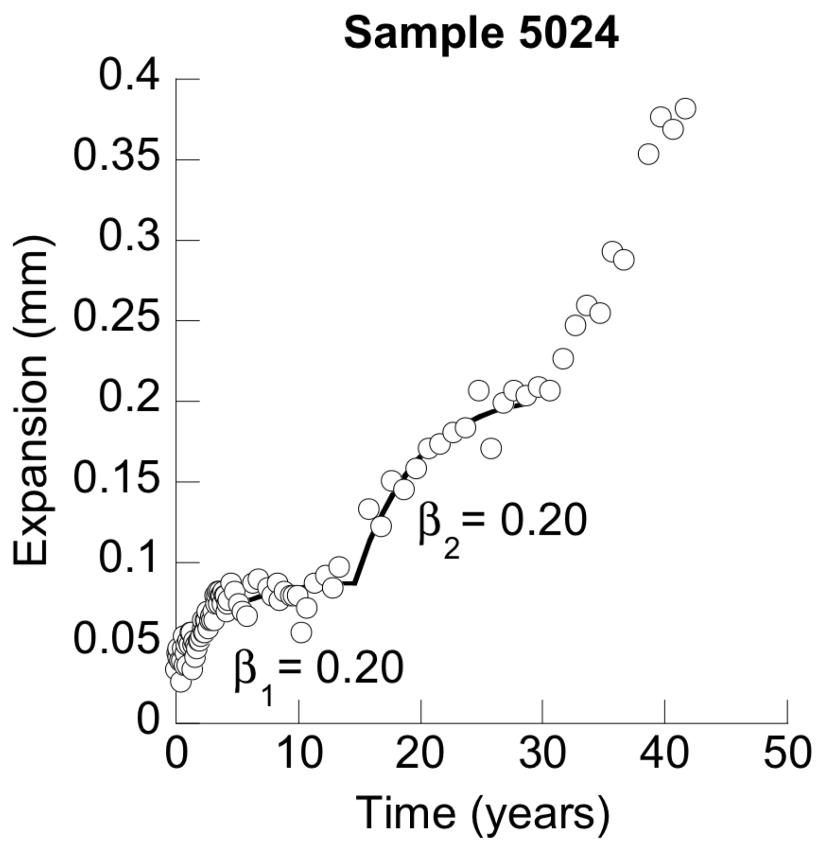
In the coordinates $\varepsilon/\varepsilon_i$ and $(t - t_o)/(t_i - t_o)$, after a period of time $(t_i - t_o)$ the experimental points follow a straight line confirming the form of the scaling law. The slope depends on the cement composition but not on the water-to-cement ratio.

Saturation periods

- When the concrete samples were cast with very low water-to-cement ratio, periods of saturation. It seems that after 30 years, scaling laws may start to develop.
- The mathematical expression used to fit the experimental results for each of the saturation periods is as follows:

$$\Delta L = \varepsilon_{\lim} \left(1 - e^{-\beta\, t}\right)$$

Development of a saturation process for concrete made with low water-to-cement ratio



Effect of the type of cement

- Next figure shows that the value for alpha more than doubles when cement with high amount of $Ca_3Al_2O_6$ are used.
- Concrete samples cast using these cements failed in a short period of exposure to sulfate solution.

Development of self-similar behavior for concrete exposed to sulfate solution. The cement used in sample 1005 had 11% of C_3A

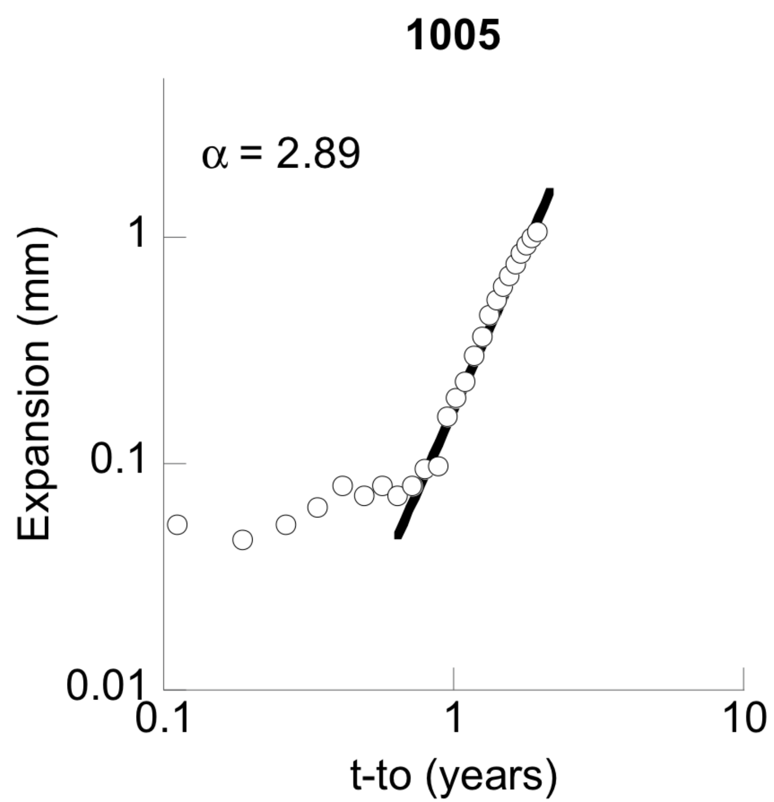


Table 2. Summary of the experimental results (effect of cement composition)

Sample	w/c	C_3A, %	C_3S, %	C_2S, %	C_4AF, %	α	t_o, years	t_i, years
1003	0.51	11	58	15	6	2.91	−0.01	0.68
1004	0.51	11	58	15	6	2.85	0.00	0.72
1005	0.51	11	58	15	6	2.89	−0.04	0.72
1006	0.49	11	65	9	8	3.23	0.04	0.4
1007	0.49	11	65	9	8	3.39	0.21	0.6
1008	0.49	11	65	9	8	3.38	0.10	0.4
1018	0.48	5	36	41	11	1.17	0.38	6
1019	0.48	5	36	41	11	1.14	2.41	6.65
1111	0.48	6	74	3	10	2.35	−0.08	1.07
4054	0.49	4	48	30	10	1.31	0.99	5.8
4055	0.49	4	48	30	10	1.36	−0.45	5.1
4057	0.51	4	48	30	10	1.41	0.23	5.01
4058	0.51	4	48	30	10	1.42	0.24	4.8

w/c, water-to-cement ratio.

Correlation between alpha and the cement minerals

$$\alpha = 0.0252 \quad \frac{C_3A^{0.643}\ C_3S^{0..953}}{C_4AF^{0.314}}$$

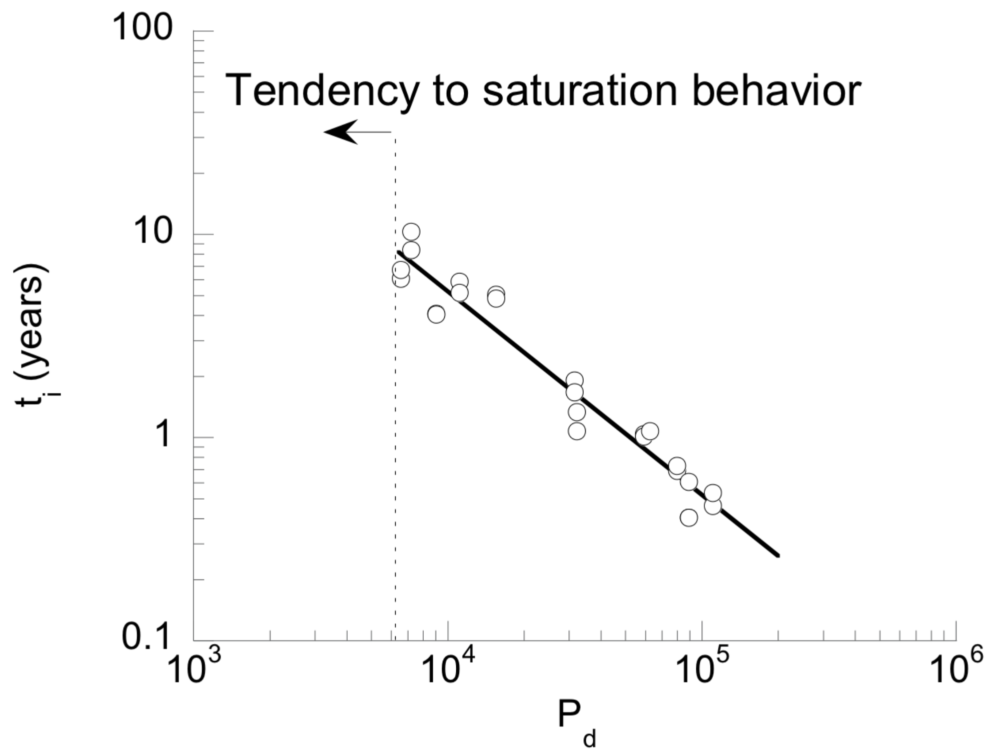
Correlation between initiation time and the cement minerals

$$t_i = \frac{52522}{C_3A^{1.39}\ C_3S^{2.90}\ C_4AF^{0.77}\ wc^{7.80}}$$

Potential for Damage (P_d)

$$P_d = C_3A^{1.39}\ C_3S^{2.90}\ C_4AF^{0.77}\ wc^{7.80}$$

Relationship between the potential for damage factor Pd and the initiation time



Observations

- As the values of P_d decreases below 3500 the concrete samples have a saturation curve behavior.

Observations

- For instance, samples 5024 and 7041 showed strong saturation curves and did not failed over the 40 plus years of the immersion test had P_d values of 2965 and 1482, respectively.

Observations

- On the other hand, sample 1111 with a P_d value of 63019 and sample 1005 with a P_d of 80767 failed in 3.8 and 2.0 years respectively.