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A new technique for the measurement of the electrical resistivity of concrete

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The measurement of electrical resistivity is quite important in the study of concrete properties, since it provides information on permeability and hence the durability and strength. In addition, the rate of transport of aggressive ions like chlorides and sulphates, which lead to corrosion of the reinforcing steel, is controlled by permeability. In this Paper a simple and elegant technique for measuring the electrical resistivity of concrete is described. The method consists in the application of a current pulse to the steel–concrete system immersed in an electrolyte, and measuring the amplitude of the potential step, either using an oscilloscope or a digital voltmeter through an interface circuit. Using this technique the variation of the resistivity of concrete has been measured as a function of the curing time. The resulting curve has been found to follow a hyperbolic expression; this is correlated with the curve of the variation of compressive strength with time.

Introduction

It is well known that the electrical resistivity of concrete is related to its permeability.[1] Permeability is a fundamental property of concrete that to a great extent decides its durability and strength, since it is well known that the permeability is inversely proportional to the strength.[2] Hence, a measurement of resistivity can provide information on the strength of the material. Further, resistivity is also a measure of ionic diffusion under electrical potential gradient. The rate of transport of ions like chloride and sulphate through concrete has an important bearing on the rate and degree of deterioration of reinforcing steel. It is the permeability which to a large extent controls the extent of the corrosion, since it is caused by the ionic content near the steel surface. Hence, the measurement of resistivity provides information on the corrosion behaviour of reinforcing steel.

A knowledge of electrical resistivity is important in understanding the initial setting and subsequent hardening of concrete, and also in determining the heterogeneity of the mix. The variation in the resistivity of cement with time is related to the hydration of the cement paste, and is indicative of the rate at which the chemical reactions occur within the paste. Owing to this, the resistivity of cement also exhibits age dependency.

Process of current conduction through concrete

The electrical resistivity of any material is defined as the resistance (ohm) between opposite faces of a unit cube of the material. Thus, if R (ohm) is the resistance of a specimen with length L (m) and cross-sectional area A (m^2), the resistivity ρ is expressed by

$$\rho = RA/L \quad \Omega\text{m} \tag{1}$$

The electrical current is conducted in concrete through: the paste; the aggregate and paste in series; the aggregate particles in contact with each other. Hence, the resistivity of saturated concrete depends on the microstructure, the pore size distribution and continuity of pores, and the composition of the pore electrolyte solution.

Measurement of electrical resistivity

Since any application of direct current (DC) through a cross-sectional area and length of concrete produces polarization of the electrode, this method

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cannot be applied for measuring the resistivity of concrete. Hence, the measurement of resistivity is usually carried out by applying high-frequency (1000 Hz) alternating current (AC), at which polarization effects are negligible.[3]

In this Paper the Authors describe a simple and elegant method for measuring the electrical resistivity by decoupling resistance and polarization components. The method, known as the galvanostatic charging techniques,[4,5] consists in the application of a train of rectangular current pulses of short duration (5–10 ms) through a galvanostat to the specimen, which acts as a working electrode and is kept immersed in an electrolyte. The potential–time response consists of a fast rising portion of ohmic component and a slowly rising polarization component. The step response can be easily observed and measured. The ratio of the step potential and the applied pulse current gives the resistance of the specimen.

Experimental

Preparation of the specimen

High-tension steel of 5 mm diameter was used for embedment. It was first cleaned thoroughly to remove all rust and other adherent oxide films, and later dipped in concentrated hydrochloric acid to remove all traces of oxide film. This was then cleaned, dried and degreased in acetone. A known length of the reinforcement was exposed to concrete. The remaining portion was made non-conducting by using a PVC tape. A typical specimen used for the resistivity experiment is shown in Fig. 1.

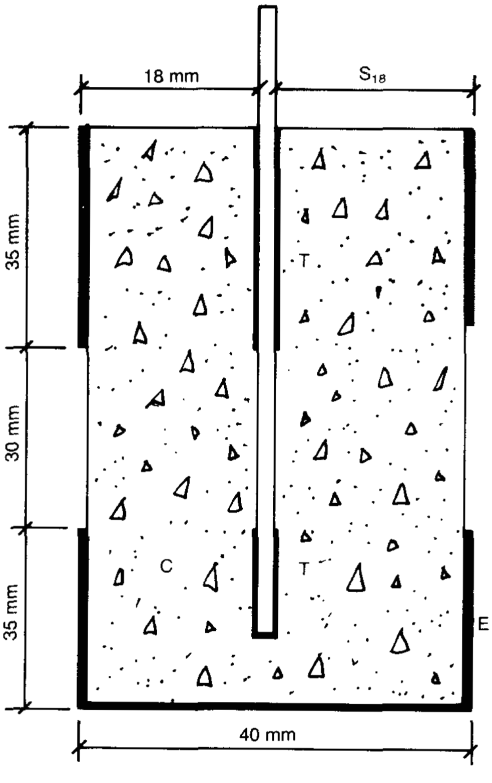

Fig. 1. Typical reinforced concrete specimen used for resistivity measurements: S steel, T tape for insulation, E epoxy coating, C concrete

The following concrete mix proportions were used

(*a*) 1 : 2 : 3 (M15); w/c = 0·5% wt
(*b*) 1 : 1·5 : 3 (M20); w/c = 0·4% wt
(*c*) 1 : 1 : 2 (M25); w/c = 0·4% wt
(*d*) 1 : 3 (mortar); w = 10% wt

The resistivity measurement was carried out in saturated calcium hydroxide + 0·1 M sodium hydroxide, after keeping the samples immersed for about 1 h. This ensured that the concrete specimens were fully flooded.

In addition to the periodic monitoring of resistivity using the above concrete mixes, the following additives were also tested for their effects on resistivity change with age. The additives were selected on the basis of their proven abilities to modify the pore distribution in concrete

(*a*) water-proofing compound
(*b*) $CaCO_3$ (2%wt) as pore filler
(*c*) sodium lauryl sulphate
(*d*) calcium chloride

Studies were conducted using concrete specimens with different heights and cover thicknesses.

Instrumentation

The current pulse from a pulse generator is applied to the cell through a galvanostat. The potential response is measured at the working electrode with respect to SCE using an instrumentation amplifier, as shown in Fig. 2. The potential–time response is monitored either on an oscilloscope at maximum sensitivity range to measure the step height, or alternatively a simple circuit such as that shown in Fig. 3 can be used. In this circuit the potential–time response is sampled by two sample-and-hold amplifiers SH1 and SH2, one before the rise of the transient and another immediately after the step response; a time delay of 50 μs separates the two samples. The voltage difference between the two sampled values corresponds to the step height which can be measured using an operational amplifier adder and a digital voltmeter (DVM).

Results and discussions

Variation of resistance with area

Figure 4 shows a plot of the variation of resistance with height of the concrete specimens (1 : 1 : 2 M25 mix). A concrete cover thickness of 17·5 mm with HTS steel embedded in it was used for the resistance measurement. Since the cover thickness is the same for all the specimens, a linear plot showing the decrease of resistance with area is obtained. This shows that the

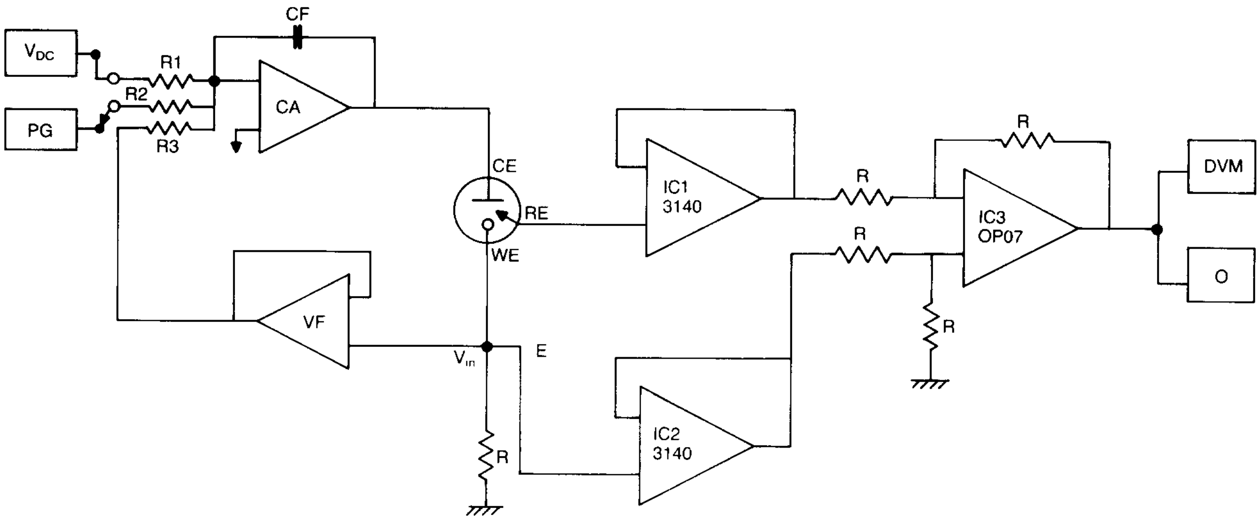

Fig. 2. Circuit for measuring the ohmic drop using an oscilloscope: PG pulse generator; CA control amplifier; VF voltage follower; IC1, IC2, IC3 operational amplifiers; R1, R2, R3, R resistivities; CF capacitance; CE, RE, WE counter, reference and working electrodes; O oscilloscope

permeability is a function of the area, and is almost uniform throughout the specimen.

Resistivity measurement at different cover thicknesses

The resistivity measurements were carried out at various cover thicknesses. The diameters of the concrete specimens used were 110, 90, 75, 63, 50, 40 and 32 mm, with corresponding cover thicknesses of 52·5, 42·5, 35, 29, 22·5, 17·5 and 13·5 mm. Epoxy was applied at the bottom of each specimen to prevent electrolyte solution from reaching the metal through the bottom portion.

The concrete resistivity ρ_c is given by

$$\rho_c = RA/L \qquad (2)$$

where R, A and L are the resistance, area and cover thicknesses, respectively. If the cover thickness L is very much less than the radius of the steel reinforcement then

$$\begin{aligned}\rho_c &= R2\pi Lh/L \\ &= \rho_c/2\pi h \qquad (3)\end{aligned}$$

where h is the height of the concrete cover. In other words, the resistance is independent of the cover thickness of the concrete.

Table 1 shows the resistance and resistivity values obtained for different thicknesses of the specimen after one day of curing. These values show a scatter within ±7%. This shows that the permeability and

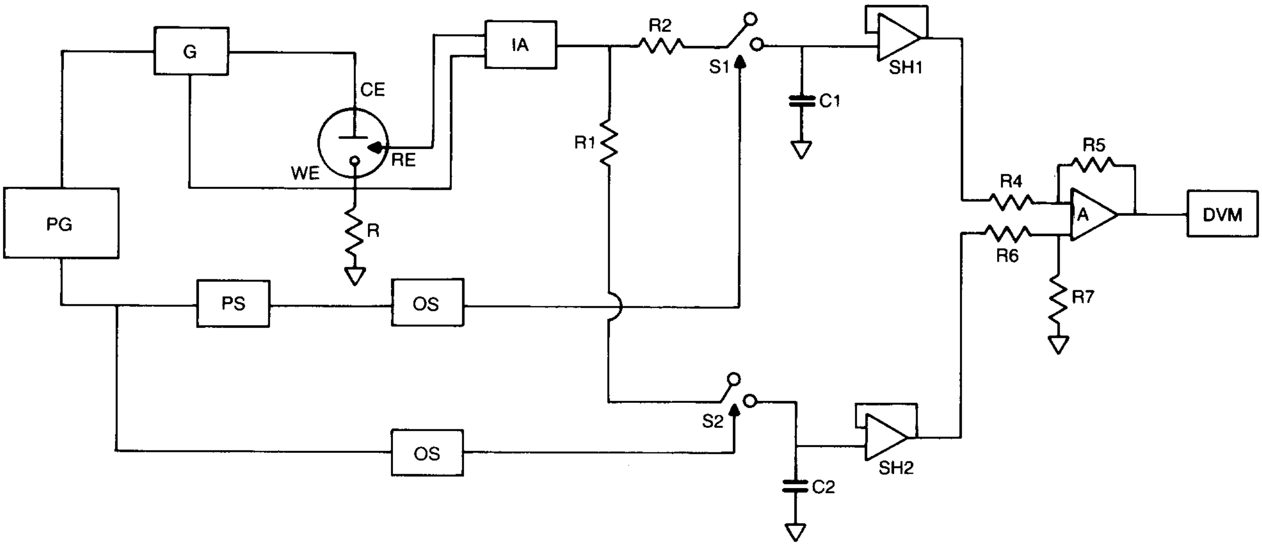

Fig. 3. Circuit for measuring the ohmic drop using a digital voltmeter: PG pulse generator; G galvanostat; WE, CE, RE working, counter and reference electrodes; IA instrumentation amplifier; PS phase shifter, OS one shot; S1, S2 analogue switch CD4016; C1, C2 capacitors; A adder; SH1, SH2 sample and holds

Table 1. Resistance and resistivity values of M25 specimens of different cover thicknesses (after one day of curing)

Diameter: mm	Cover thickness: mm	Resistance: Ω	Resistivity: Ωm
110	52·5	64	42·15
90	42·5	62	41·25
75	35·0	59	39·70
63	29·0	56	38·25
50	22·5	53	37·00
40	17·5	54	38·80
32	13·5	58	43·20
		Av. 58	Av. 40·05

pore size distribution remain constant for a cover thickness ranging from as small as 13·5 mm to as large as 52·5 mm. The results confirm the validity of using resistivity measurement as an indirect indicator of the permeability and the pore size distribution of concrete.

Effect of ageing on the electrical resistivity of concrete

In a fresh cement paste the flow of water is controlled by the size and shape of the original cement grains. The permeability decreases with the progress of hydration, since the gel fills the space originally occupied by water. Hence, the resistivity, which is inversely proportional to the permeability, increases with age. Since the resistivity is related to the degree of hydration of the cement paste within the mix, it must be an indirect measure of the strength at any particular point of time.

From Table 2 it can be seen that the resistivity increases rapidly in the beginning for the first fifteen days for M25 specimens. In the case of mortar and M15, the resistivity values show an appreciable increase only after 10 days of curing. This is due to the lower cement content in these specimens compared to specimens of M20 and M25 grade. Hence, the progress of hydration is also slow. Although the addition of 2–3% waterproofing compound increases the resistivity substantially, a larger addition has no influence. This may be due to the decrease in the cement content which leaves the porosity of the concrete rather high. Calcium carbonate has marginally increased the resistivity, whereas $CaCl_2$ decreases it. The latter is due to the increased conductivity caused by chloride ions. Obviously, when the ionic contents inside the pores and voids are high, the resistivity values cannot be considered as completely reflecting the extent of the porosity of the concrete. Long-chain fatty compounds such as stearates, soaps, etc., are known to be effective pore filters in concrete.[2] In this Paper the Authors have used sodium lauryl sulphate as a pore filler. It can be seen that the addition of lauryl sulphate has effectively filed the pores, as evidenced by the increase in resistivity. Since sodium lauryl sulphate would also be an effective air entrainer, it has modified the void distribution within the concrete.

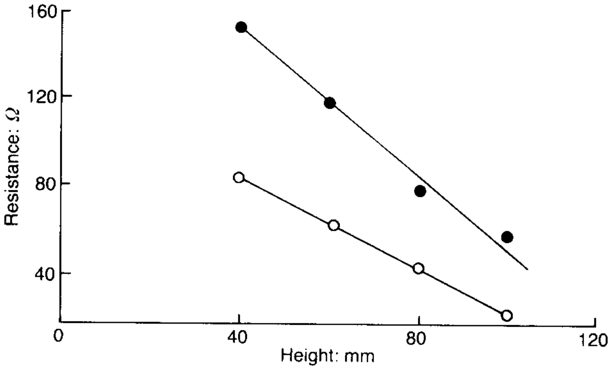

Fig. 4. Variation of resistance of concrete specimens (1 : 1 : 2 M25 mix) with height: ○ 1 day of curing; ● 3 days of curing

Figure 5 shows a typical resistivity curve plotted against the number of days of curing. It can be seen that the resistivity increased steeply at the beginning and asymptomatically approached an upper limit after a curing period of 25 days. The shape of the curve suggests that it may follow a hyperbolic fit of the form

$$y = x/(ax + c) \tag{4}$$

Table 2. Variation of electrical resistivity (Ωm) with age in different types of mixes

Mix	No. of days									
	1	3	4	5	8	10	17	20	24	28
Mortar (1 : 3)	9·4	11·3	11·3	13·2	15·1	14·1	18·8	19·8	18·8	23·7
M15	13·2	17·0	18·8	18·9	18·9	22·6	24·5	25·5	28·3	30·2
M20	17·0	26·4	30·2	—	30·2	—	32·0	32·9	33·9	37·7
M25	30·2	—	42·8	58·4	67·9	67·90	75·4	82·9	90·5	90·5
M25 + 2% WP	33·9	50·9	56·5	60·3	60·3	73·5	86·7	90·5	98·0	98·0
M25 + 3% WP	37·7	54·6	60·3	64·1	81·1	82·9	94·2	101·7	105·6	105·6
M25 + 5% WP	33·9	45·2	50·9	52·8	62·2	66·0	69·7	79·2	84·8	90·5
M25 + 2% LS	33·9	50·9	60·3	67·8	75·4	79·2	88·6	94·3	105·6	105·6
M25 + 2% $CaCO_3$	30·2	43·3	49·0	54·6	60·3	67·9	79·2	82·9	94·25	98·0
M25 + 2% $CaCl_2$	30·2	—	49·0	49·0	55·6	66·0	79·2	—	79·2	90·5

$\rho_c = 2R \times \pi \times 30 \times 10^{-3} = 0{\cdot}1885R\,\Omega\text{m}$

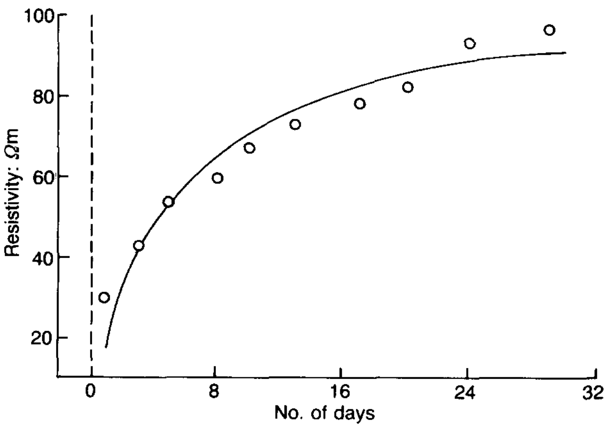

Fig. 5. A typical plot of resistivity versus number of days of curing

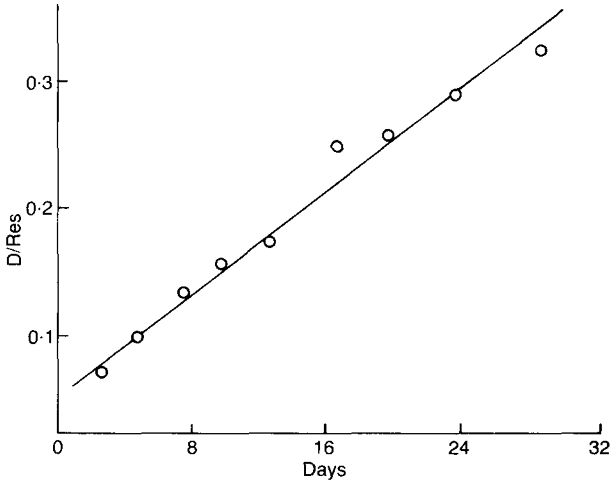

Fig. 6. Hyperbolic fit of the plot of resistivity versus number of days of curing for M25 mix: $y = x/(0{\cdot}01x + 0{\cdot}036)$; correlation coefficient 0·989; D number of days, RES resistivity

Hence, a plot of x/y versus x will yield a straight line with slope a and intercept c if the hyperbolic fit is adopted. Such a plot is shown in Fig. 6. A correlation coefficient of 0·989 was obtained for this curve. From the plot, the slope $a = 0{\cdot}0103$ and the y intercept $c = 0{\cdot}03603$ were obtained.

In order to check whether a and c were unique to a particular mix proportion, specimens of the same concrete mix but different cover thicknesses were used for resistivity measurements. The resistivity data are presented in Table 3 for specimens curved for 1 and 14 days. The data for 14 days are chosen because they are half-way through the ascending portion of the curve, and hence an ideal choice for testing the validity of the equations and constants obtained. The theoretical resistivity values obtained using equation (4) are also shown in Table 3, along with the percentage deviation for individual specimens. It can be seen that the deviation is less than $\pm 9\%$. Considering the fact that the resistivity values were determined for a wide range of cover thicknesses, these results conclusively prove that the resistivity varies as a hyperbolic function of the curing time.

Table 4 presents constants a and c with additivies such as a different percentage of waterproofing compound, sodium lauryl sulphate, $CaCO_3$ and $CaCl_2$. It can be seen that the constants a and c are more or less the same with different additives, and the minor variation corresponds to the small variation in 28 day resistivity values.

Table 4 also shows the constants a and c for mortar, M15, M20 and M25 specimens. The constant c varies in the order M25 < M15 < mortar. It is also found that the constant a varies inversely with the 28 day resistivity value.

Resistivity and compressive strength

Since the resistivity of concrete is an indicator of permeability and pore distribution, it is also a measure of compressive strength of concrete.[2] To find out whether the variation of compressive strength with time follows the same hyperbolic function as the resistivity, a hyperbolic fit of the data of compressive strength versus time presented in Reference 2 was carried out. Fig. 7 shows a plot of compressive strength/number of days versus the number of days. From the straight-line fit it is evident that the com-

Table 3. Resistivity (Ω m) of specimens cared for 1 and 14 days, and of different cover thickness

Diameter of specimen: mm	Cover thickness: mm	1-day actual resistivity	14 days		Variation: %
			Actual resistivity	Theoretical resistivity	
110	52·5	42·15	78·98	77·08	+2·4%
90	42·5	41·25	79·83	77·08	+3·5%
75	35·0	39·70	70·63	77·08	−8·3%
63	29·0	38·25	71·66	77·08	−7·03%
50	22·5	37·00	73·00	77·08	−4·9%
40	17·5	38·80	75·40	77·08	−2·18%
32	13·5	43·20	81·91	77·08	−6·26%

Theoretical resistivity = $14/(14(0{\cdot}010381) + 0{\cdot}0360)$

Table 4. Constants a and c (in $y = x/(a\,x + c)$ and R-squared values for different specimens

Type of mix	R-squared	*a*	*c*
Mortar (1:3)	0·946	0·04138	0·193114
M15	0·958	0·31615	0·122144
M20	0·984	0·26473	0·055170
M25	0·989	0·010381	0·036029
M25 + 2% WP	0·981	0·009086	0·038760
M25 + 3% WP	0·991	0·008471	0·031479
M25 + 4% WP	0·991	0·010201	0·036902
M25 + 5% WP	0·981	0·010372	0·038944
M25 + 2% LS	0·985	0·008590	0·034627
M25 + 2% $CaCO_3$	0·978	0·009149	0·046682
M25 + 2% $CaCl_2$	0·990	0·010898	0·041324

pressive strength varies as a hyperbolic function of time. It is worth pointing out here that the resistivity which is a measure of compressive strength also varies in the same manner.

Conclusion

The measurement of the electrical resistivity of concrete provides information on the porosity and pore size distribution within concrete. In this Paper a simple and elegant technique for measuring the concrete resistivity based on the galvanostatic charging technique has been proposed and tested for several concrete mix proportions and cover thicknesses. The results show that the resistivity varies as a hyperbolic function of the number of days of curing. The constants *a* and *c* in the expression relating the resistivity and the number of days of curing have been found to be unique to any particular mix proportion.

The technqiue described here and shown to work with specimens in the laboratory conditions could in principle be extended for application in actual field conditions. Further work is in progress in this regard.

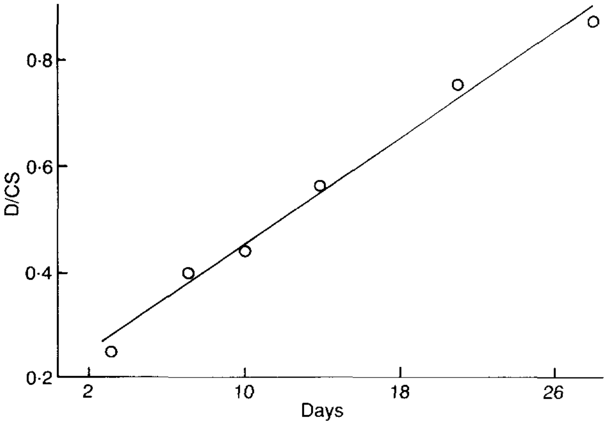

Fig. 7. Plot of compressive strength/number of days versus number of days: D = number of days; CS = compressive strength

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