SPALLING

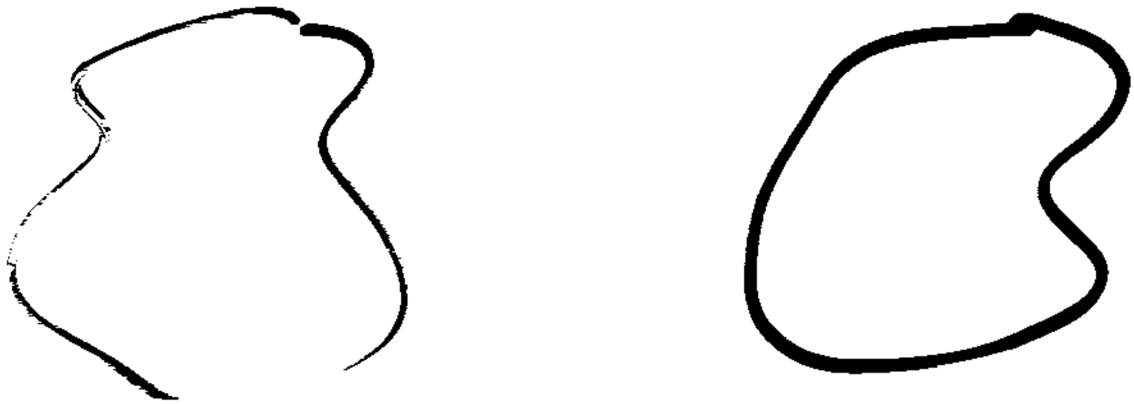
OF CONCRETE

IN FIRE

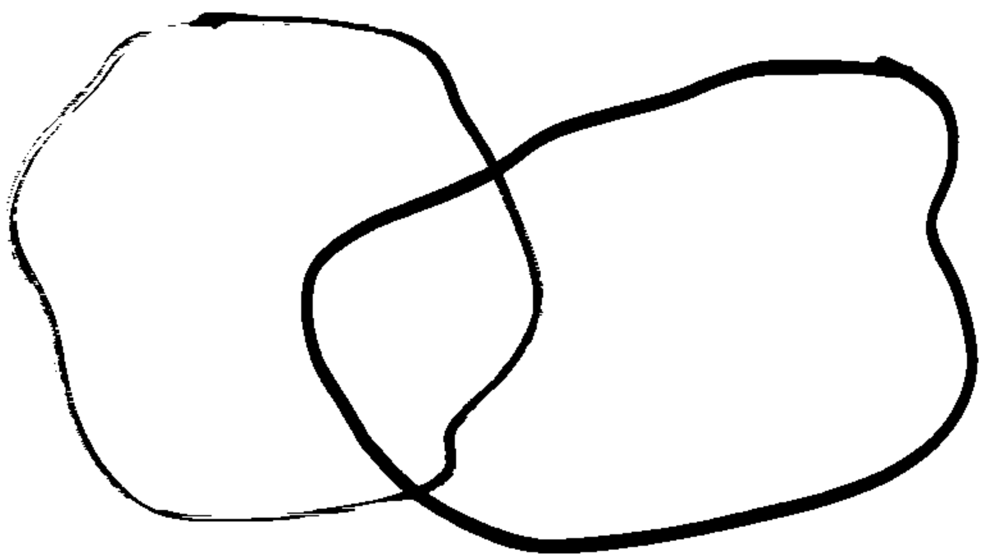
John Purkiss

ALTERNATIVELY

PORE PRESSURE STRESS



BUT



MODELLING REQUIRES

a) COUPLED HEAT AND MASS TRANSFER

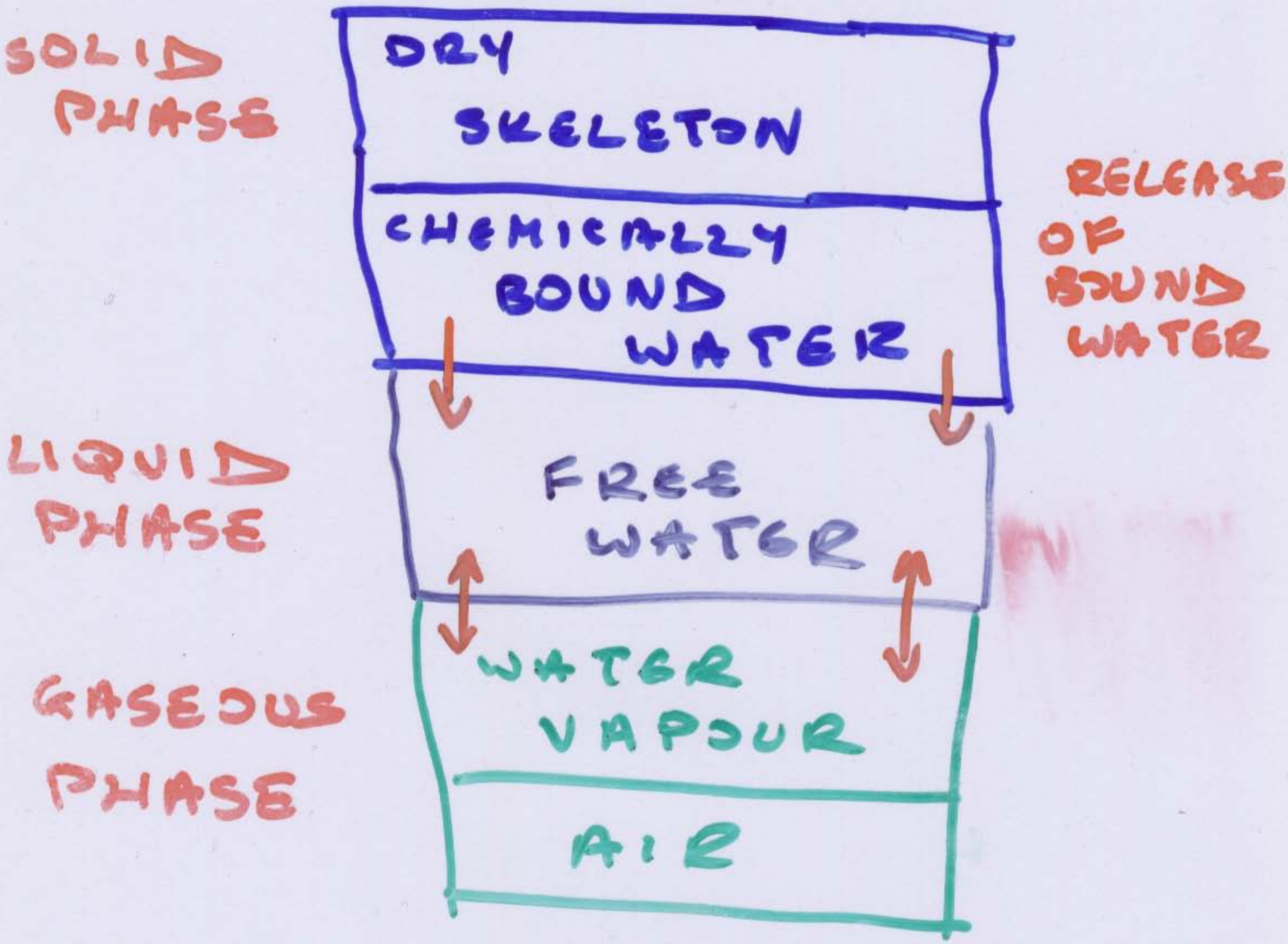
b) COUPLED STRESS AND HEAT/MASS TRANSFER

c) FAILURE CRITERION

d) CONCRETE STRESS-STRAIN MODEL- MUST INCLUDE TRANSIENT STRAIN

- MOISTURE CONTENT
- CONCRETE POROSITY
- PORE SIZE DISTRIBUTION
- PERMEABILITY
- AGGREGATE TYPE
- SECTION PROFILE & COVER
- HEATING RATE
- CONCRETE STRENGTH

MODEL


SOLID PHASE
DRY SKELETON
CHEMICALLY BOUND WATER
RELEASE OF BOUND WATER
LIQUID PHASE
FREE WATER
GASEOUS PHASE
WATER VAPOUR
AIR

COUPLED HEAT/MASS TRANSFER

REQUIRES SOLUTION OF

- Water conservation
- Water vapour conservation
- Air conservation
- Energy conservation
- Fick's Law
- Darcy's Law
- Ideal Gas Equation
- Volume ratios
- Release of bound water

These give 17 equations- but there are 18 variables.

The last equation is either

- Sorbtion curves
  (relate amount of liquid water to temperature and partial pressure of water vapour)

Or

- Rate of Evaporation

No real difference in final results

FAILURE CRITERIA:

- ASTON

TENSILE STRESS CRACKING CRITERION

CRACKS ARE THEN ASSUMED TO JOIN FAILURE NODES

STRESS INTENSITY FACTOR INCLUDED

FRACTURE CRITERION BAASED ON FRACURE TOUGHNESS

- WARWICK

BASED ON ORTIZ

[MORE COMPLEX]

PROBLEMS:

- Porosity increases with temperature

  8 times higher at 800°C

  Empirical equation used

- Permeability increases

  Assumed to be related to increase in pore volume

  Can be assumed to be related to local temperature reduced concrete strength

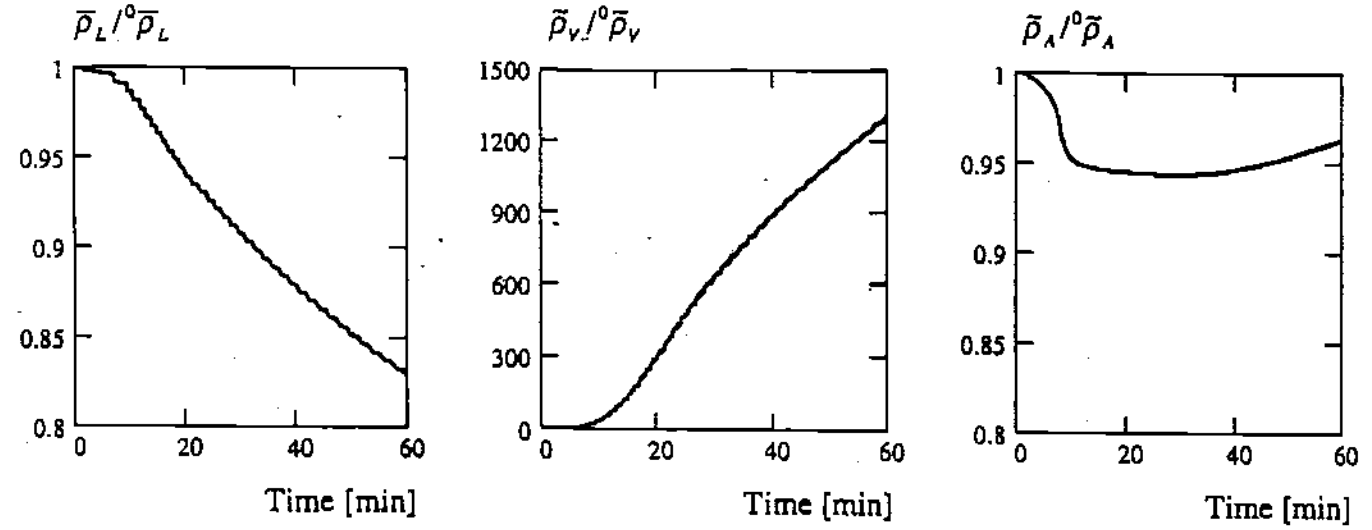


Figure 5. Relative content of liquid water, $\bar{\rho}_L/{}^0\bar{\rho}_L$; water vapor, $\bar{\rho}_V/{}^0\bar{\rho}_V$, and air, $\bar{\rho}_A/{}^0\bar{\rho}_A$, after 60 minutes of exposure to fire.

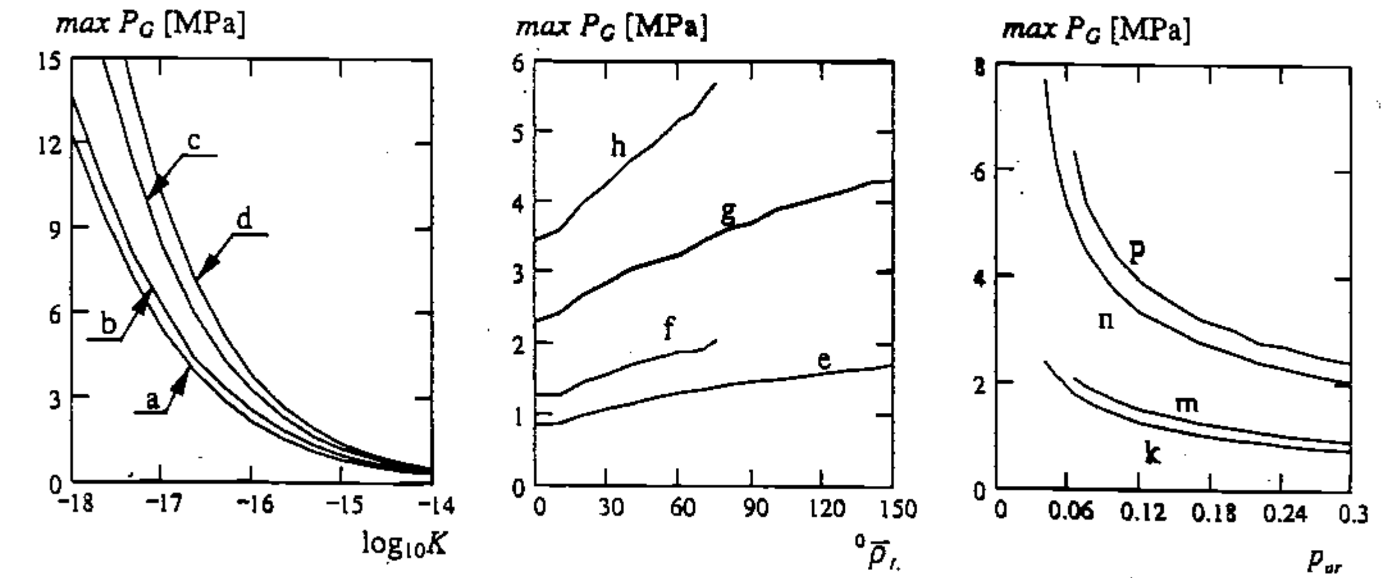


Figure 6. Influence of permeability, K [m^2], initial water content, ${}^0\bar{\rho}_L$ [kg/m^3], and porosity, p_{or}, on maximum pore pressure P_G [MPa] after 20 minutes of fire exposure. a: ${}^0\bar{\rho}_L = 30$, $p_{or} = 0.16$; b: ${}^0\bar{\rho}_L = 60$, $p_{or} = 0.16$; c: ${}^0\bar{\rho}_L = 30$, $p_{or} = 0.08$; d: ${}^0\bar{\rho}_L = 60$, $p_{or} = 0.08$; e: $K = 5 \times 10^{-16}$, $p_{or} = 0.16$; f: $K = 5 \times 10^{-16}$, $p_{or} = 0.08$; g: $K = 5 \times 10^{-17}$, $p_{or} = 0.16$; h: $K = 5 \times 10^{-17}$, $p_{or} = 0.08$; k: ${}^0\bar{\rho}_L = 30$, $K = 5 \times 10^{-16}$; m: ${}^0\bar{\rho}_L = 60$, $K = 5 \times 10^{-16}$; n: ${}^0\bar{\rho}_L = 30$, $K = 5 \times 10^{-17}$; p: ${}^0\bar{\rho}_L = 60$, $K = 5 \times 10^{-17}$.

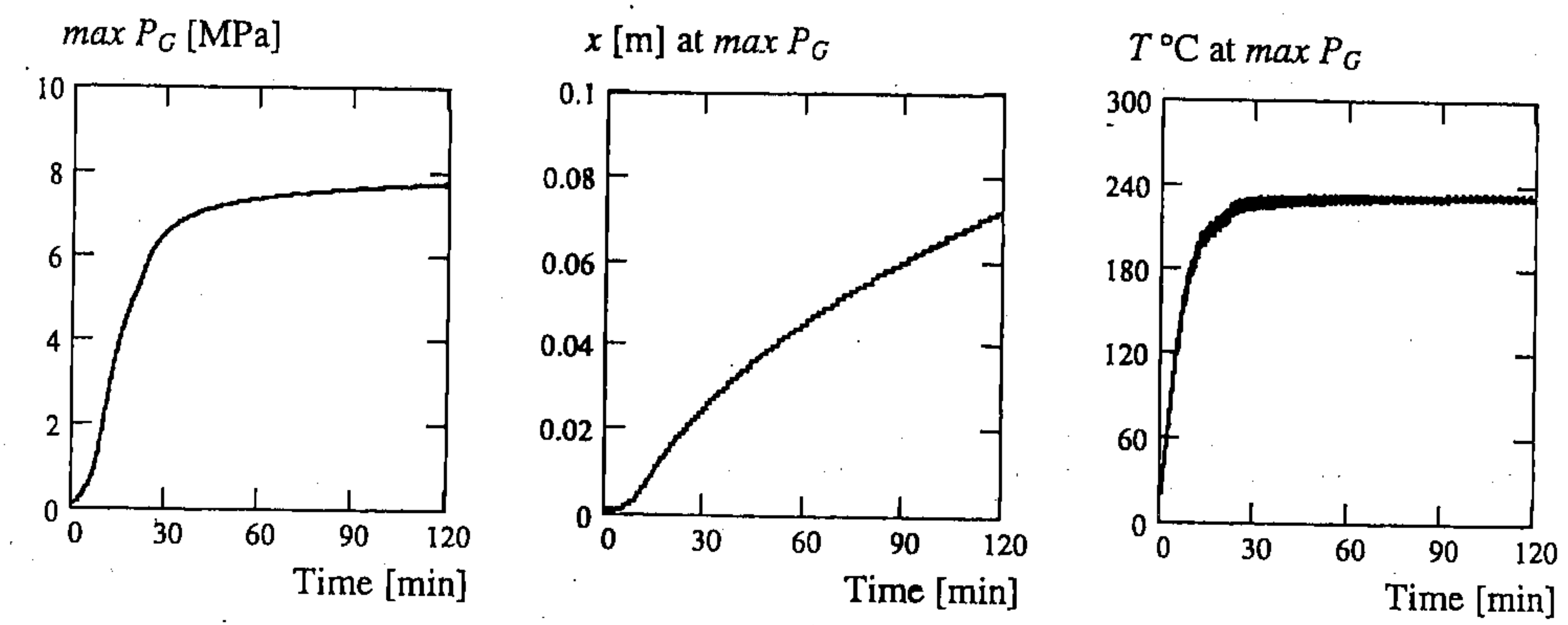
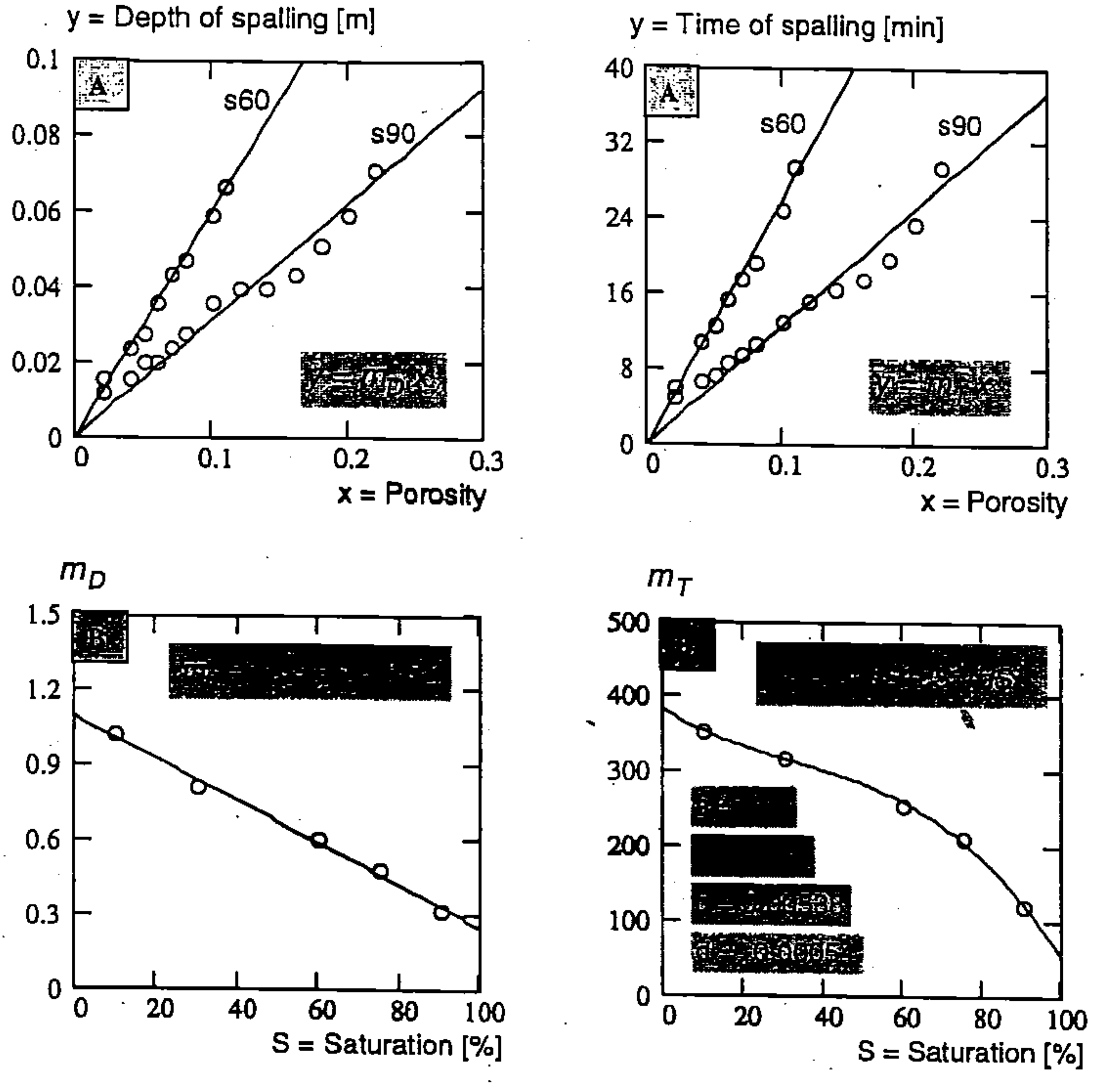
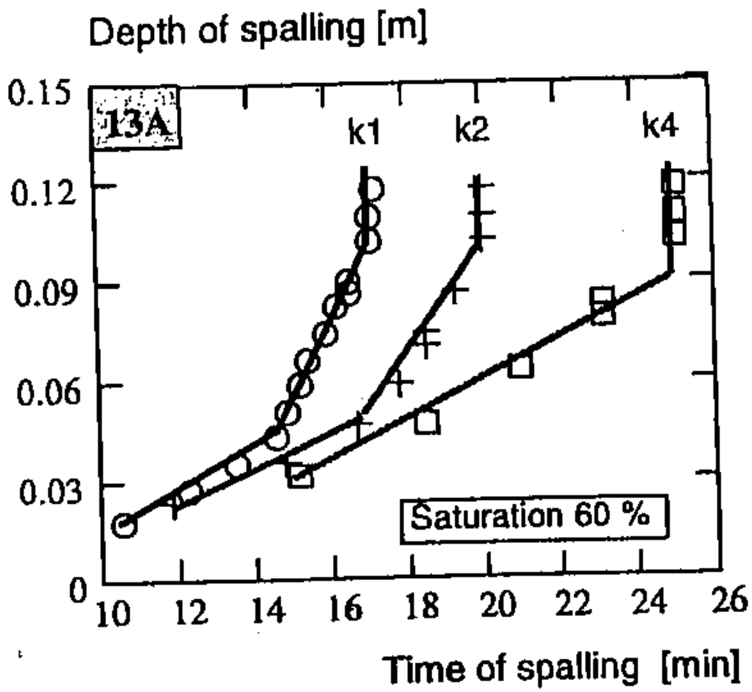


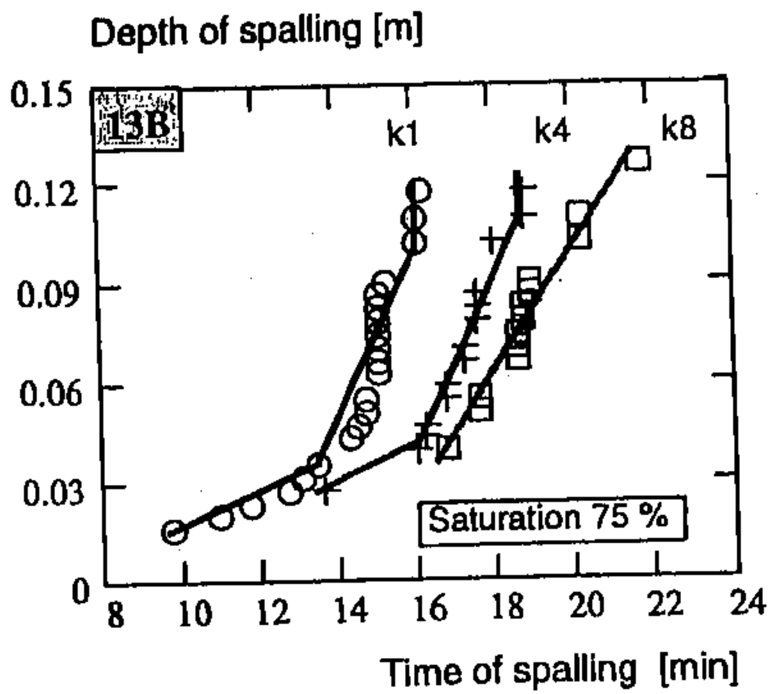
Figure 4. Maximum pore pressure, max P_G [MPa], its location, x [m], from the fire exposed surface and the temperature T [°C] at x as function of time.


y = Depth of spalling [m]
A
s60
s90
[redacted]
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
x = Porosity
y = Time of spalling [min]
A
s60
s90
[redacted]
40
32
24
16
8
0
0
0.1
0.2
0.3
x = Porosity
m_D
[redacted]
1.5
1.2
0.9
0.6
0.3
0
0
20
40
60
80
100
S = Saturation [%]
m_T
[redacted]
500
400
300
200
100
0
0
20
40
60
80
100
S = Saturation [%]

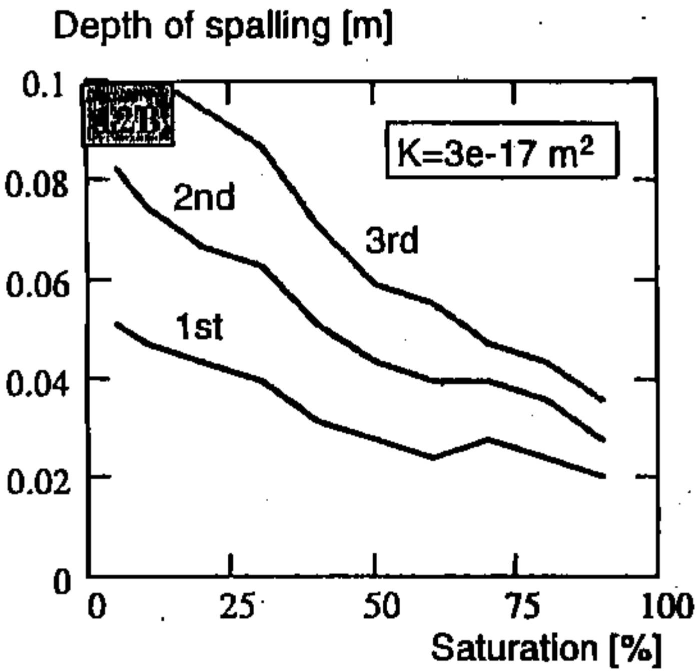
SATURATION 60%

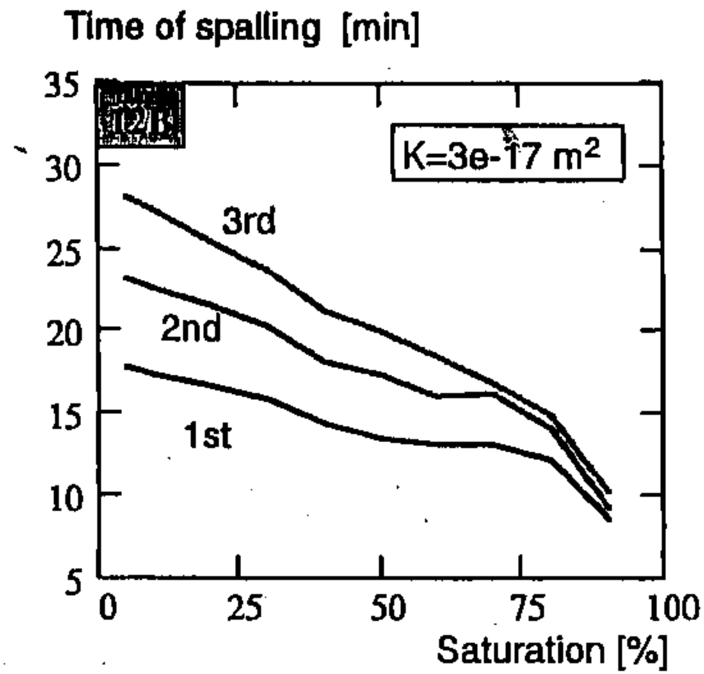


SATURATION 75%

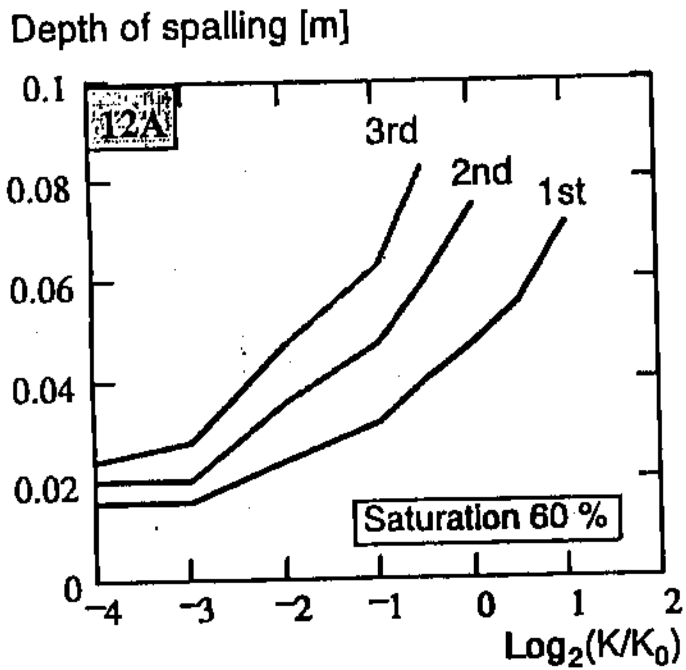


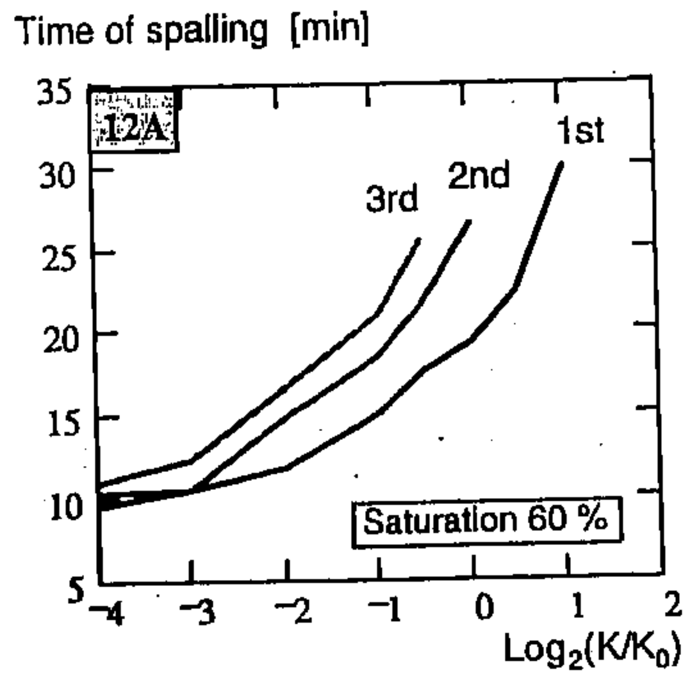
k1: 1×10^{-17} m²   k2: 2×10^{-17} m²   k8: 8×10^{-17} m²





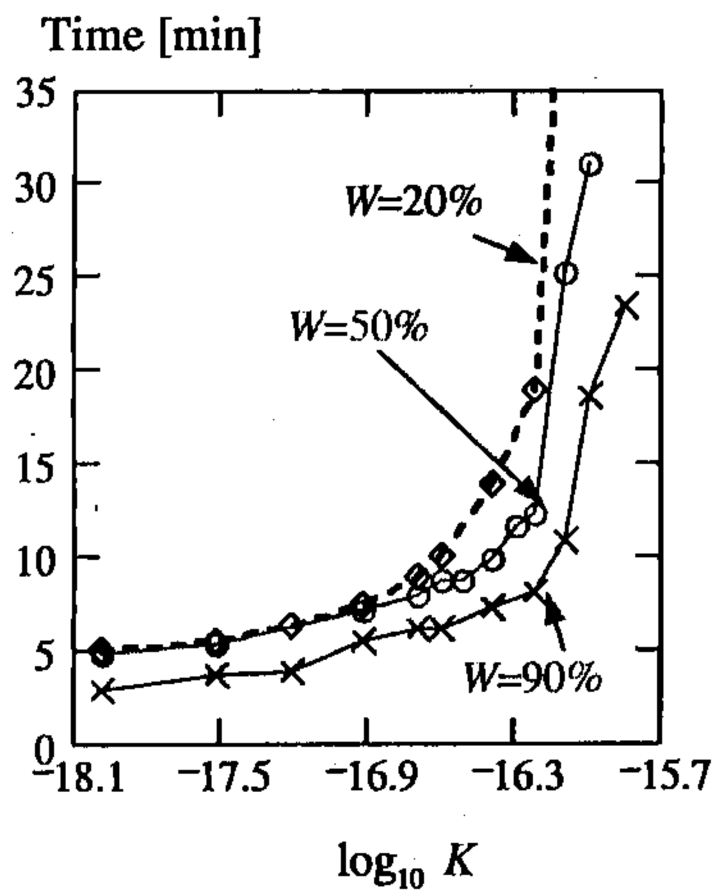
$$K = 3\times10^{-17}\ m^2$$

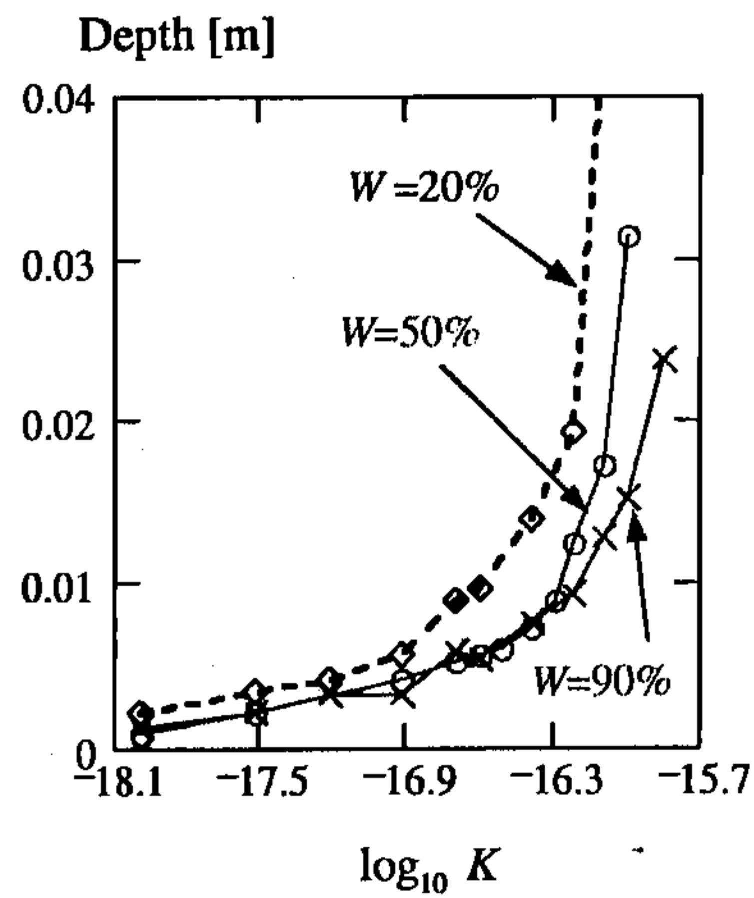




$K_0 = 8\times10^{-17}\ m^2$

SATURATION 60%


Time [min]
35
30
25
20
15
10
5
0
−18.1
−17.5
−16.9
−16.3
−15.7
log10 K
W=20%
W=50%
W=90%


Depth [m]
0.04
0.03
0.02
0.01
0
−18.1
−17.5
−16.9
−16.3
−15.7
log10 K
W=20%
W=50%
W=90%

HIGH STRENGTH CONCRETE/

SELF COMPACTING CONCRETE

- MORE SUSCEPTIBLE TO SPALLING

- POLYPROPYLENE FIBRES

NOT STEEL FIBRES

ADDITIONAL COMMENTS

- 200°C ISOTHERM IS CRITICAL
- THIN SECTIONS GENERATE HIGHER PORE PRESSURES

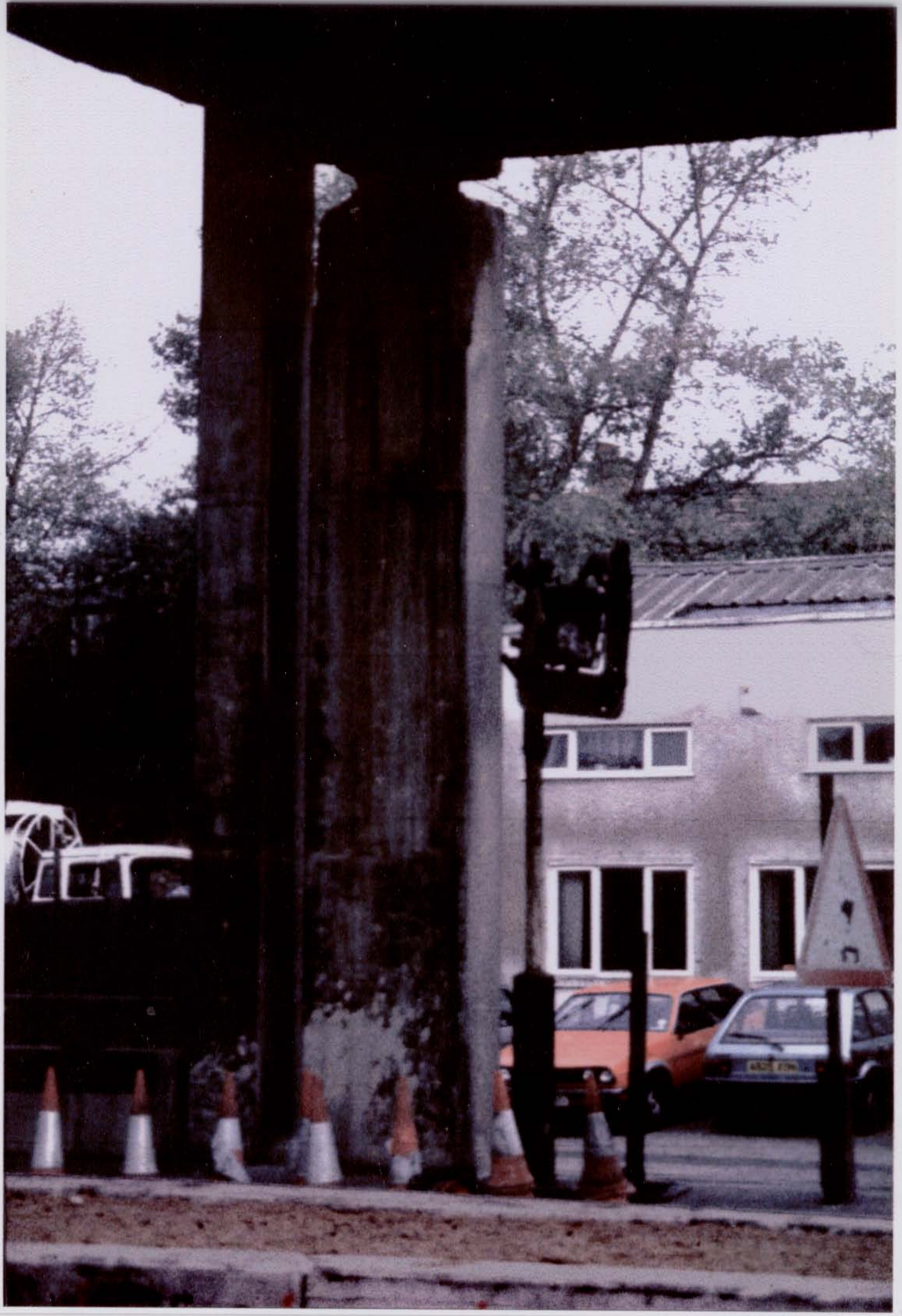
CARDINGTON:

- HIGH MOISTURE CONTENT

- PROBLEMS WITH

  “OVERSTRONG”

  CONCRETE



TYPES OF SPALLING:

- AGGREGATE SPALLING

SURFACE EFFECT

FIRST 20 mins

10 to 20 mm DEEP

- CORNER SPALLING [SLOUGHING OFF]

OCCURS LATE IN STANDARD TESTS

DUE TO:

Loss of (normal) bond

Differential thermal expansion/ restraint

- SURFACE SPALLING

Large lumps of concrete removed

Can be 100 mm square and 50 mm deep

VIOLENT

- EXPLOSIVE SPALLING

REMOVAL of LARGE AREAS

May be up to 1 m^2 [SLABS]

VERY VIOLENT

NOISY

THE LAST TWO ARE

INDISTIGUISHABLE

FOR THEIR ULTIMATE EFFECT

SPALLING WILL EITHER

- REDUCE THE CROSS SECTION

OR

- LOSE COVER

BOTH WILL REDUCE SECTION

CAPACITY

Fire resistance column test results

Concrete Grade	Reinforcement 8D12 (1,08%)	4D25 (2,33%)
C20	3 h 54 min	3 h 13 min
C50	2 h 32 min	3 h 29 min
C90	1 h 46 min(1)	1 h 29min(2)

Notes:
(1) Spalling started at 8 minutes into the test

(2) Spalling started at 12 minutes into the test

BOTH EXPLOSIVE AND SURFACE

SPALLING HAVE A NUMBER OF

FACTORS IN COMMON

BUT

THERE IS THE ISSUE OF

STRESS vs PORE PRESSURE