THE PERFORMANCE OF FABRIC PROTECTED SLOW SAND FILTERS

by

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DEDICATION

This report is dedicated to the late my father Mr. Augustin Mbwette who died suddenly on the 13/08/87. His dedication to work will always be remembered by his family in view of the fact that he died during a meeting. May his soul rest in peace.

T.S.A. Mbwette
London, 1989.

ABSTRACT

Shortly after the successful introduction of rapid sand filtration in drinking water treatment, the popularity of Slow Sand Filtration (SSF) declined both in the USA and Europe. However, since to date not less than five major European cities still use SSF as a final filtration step, its importance cannot be overlooked. In the UK, currently it is estimated that between 20-25 % of potable water is treated by SSF. One of the major drawbacks of SSF is the high operational costs caused by frequent sand cleaning and resanding if short filter run times are experienced. These can be caused by massive die-off of/ bed plugging by algae, direct filtration of very turbid water or water with excess flocs carry-over from the pre-treatment units.

This report describes an original research study carried out in order to initiate transformation of the technology of protection of SSF with Non-Woven Synthetic Fabrics (NWF) from an art to a systematic and technically acceptable engineering application in drinking water filtration. A properly selected NWF multi-layer should extend the filter run time considerably and capture the majority of impurities within the fabric depth such that routine maintenance involves cleaning of the NWF only.

A review of the history of application of SSF and the relevant fundamental filtration theory is presented prior to discussing attempts to improve the operation of SSF and selection of NWF protection as a potential untried method for this purpose. A summary of the basic chemistry and the manufacture of NWF is given before characterizing the typical commercial NWF available in the UK. A review of previous research studies done in fabric protection of SSF is presented and its shortcomings outlined. Theoretical considerations of hydraulic behaviour and filtration mechanisms in NWF are presented and the strong dependence of filterability on the specific surface postulated.

Selected typical commercial NWF were subjected to scanning electron microscopy, permeability and filtration experiments in the laboratory. Using laboratory results as a guideline, field tests were carried out with fabric protected SSF filtering long-term stored water. During these experiments it was possible to systematically select and optimize a NWF configuration which effectively protected the sand bed and extended the filter run time by a factor of up to 8.4 . Another field study which investigated the efficacy of protection of SSF receiving pre-treated river water with excess flocs carry-over showed that a different composition of NWF layers was capable of capturing all flocs and extending the filter run time by a factor of up to 4.9. Finally, protection of conventional SSF beds with NWF is recommended for small scale plants.

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CONTENTS

Page

ABSTRACT 3

ACKNOWLEDGEMENTS 4

CONTENTS 5

LIST OF TABLES 13

LIST OF FIGURES 15

LIST OF PLATES 22

LIST OF PRINCIPAL SYMBOLS AND ABBREVIATIONS 24

1. INTRODUCTION 28

1.1 Theoretical Considerations 31

1.2 Slow Sand Filtration Applications 36

1.2.1 Operational Limitations of SSF 38

1.2.2 Attempts to Offset Operational Limitations of SSF. 39

1.3 Synthetic Fabrics Chemistry and Classifications 41

1.3.1 Synthetic Fabrics Chemistry 41

1.3.1.1 Addition Polymerization 42

1.3.1.2 Condensation Polymerization 43

1.3.2 Synthetic Fabrics Classification 43

1.3.2.1 Woven Fabrics 45

1.3.2.2 Non-Woven Fabrics 45

1.3.2.3 Composites 45

1.4 Non-Woven Synthetic Fabrics (NWF) 46

1.4.1 NWF Manufacture 46

Page

1.4.1.1 Needle-felting/punching 46
1.4.1.2 Wet-bonded 47
1.4.1.3 Dry-bonded 47
1.4.1.4 Spun-bonded 48
1.4.1.5 Spun-lacing 48
1.4.2 NWF characterization 50
1.5 Previous Research Studies 53
1.5.1 Filter Run Times 53
1.5.2 Silt Retention 55
1.5.3 Filtrate Water Quality 57
1.5.4 Fabric Biology 57
1.5.5 Fabric Cleaning 59
1.5.6 Conclusion 59
1.6 Objectives of the Study 60
1.6.1 General Objectives 60
1.6.2 Specific Objectives 61

2. THEORETICAL CONSIDERATIONS OF HYDRAULIC BEHAVIOUR AND FILTRATION MECHANISMS OF NWF. 64
2.1 Fabric Geometric Properties 64
2.2 Fabric Hydraulic Properties 66
2.3 Mode of Action of NWF 76
2.3.1 Surface Filtration 76
2.3.2 Depth Filtration 76
2.3.3 Adsorptive Filtration 77
2.3.4 Biological Filtration 78
2.4 NWF Morphological Models 79
2.5 Fabric Filterability 81

Page

3. LABORATORY STRUCTURAL, HYDRAULIC AND FILTRATION CHARACTERIZATION OF FILTER MEDIA. 85

3.1 Scanning Electron Microscope (SEM) Structural Characterization of NWF. 86

3.1.1 Materials and Experimental Procedure 86

3.1.2 Results 87

3.2 Filter Media 97

3.2.1 Fabrics Cutting 97

3.2.2 Filter Media Cleaning 99

3.3 Permeability/Filtration Column 99

3.4 Permeability Experiments 102

3.4.1 Results 107

3.4.2 Discussion of Results 115

3.5 Filterability Experiments 116

3.5.1 Preliminary Tests 118

3.5.2 Filter Media and Suspension Characteristics 121

  3.5.2.1 Filtration Filter Media 121

  3.5.2.2 Suspension Characteristics 123

3.5.3 Experimental Procedures 126

3.5.4 Results 133

3.5.5 Discussion of Results 135

4. FIELD ASSESSMENT OF HYDRAULIC AND FILTRATION PERFORMANCE OF A REPRESENTATIVE RANGE OF NWF. 151

4.1 Pilot Plant Description 151

4.1.1 Reservoir Water Sources 151

4.1.2 Pilot Plant Layout 153

4.1.3 Filter Media 159

4.2 Analysis Methods 159

Page

4.2.1 Temperature 161

4.2.2 Turbidity 161

4.2.3 pH 161

4.2.4 Bacteriological Quality 161

4.2.5 Particle Size Distribution 161

4.2.6 Water POC and Chl-a 162

4.2.7 SSF Sand Profile POC, Chl-a and Silt Content 162

4.3 Raw Water Characteristics 162

4.3.1 Inlet Water Quality 166

4.4 General Conduct of Pilot Plant Tests 166

4.4.1 Filter Media Parameters Variation 171

4.5 Results 172

4.5.1 Hydraulic Performance 173

  4.5.1.1 Filter Run Time 173

  4.5.1.2 Filter Head Loss 175

  4.5.1.3 Changes in Hydraulic Characteristics of the NWF. 178

4.5.2 Water Quality Improvements/Changes 181

  4.5.2.1 Temperature 181

  4.5.2.2 pH 181

  4.5.2.3 Turbidity 181

  4.5.2.4 Bacteriological Analysis 182

  4.5.2.5 Water POC and Chl-a 182

  4.5.2.6 Particle Capture Efficiency 187

4.5.3 SSF Sand Bio-Chemical Properties 188

  4.5.3.1 Sand POC 188

  4.5.3.2 Sand Chl-a 191

Page

4.5.3.3 Sand Silt Content 191

4.6 Discussion of Results 195

4.6.1 Hydraulic Performance 195

4.6.2 Water Quality Improvements 199

4.6.3 SSF Sand POC, Chl-a and Silt Content 200

5. OPTIMIZATION OF FIELD FILTRATION PERFORMANCE OF A SELECTED NWF. 203

5.1 Pilot Plant Modifications 203

5.2 Reservoir Water Source and Quality 204

5.3 Filter Media 204

5.4 General Conduct of Tests 206

5.4.1 Sampling Frequency and Analysis Methods 206

5.5 Results 207

5.5.1 Hydraulic Performance 207

5.5.1.1 Filter Run Time 207

5.5.1.2 Filter Head Loss 208

5.5.2 Water Quality Improvements/Changes 212

5.5.2.1 Water Temperature 212

5.5.2.2 pH 212

5.5.2.3 Turbidity 212

5.5.2.4 Bacteriological Analysis 214

5.5.2.5 Water POC and Chl-a 217

5.5.2.6 Particle Size Distribution 217

5.5.3 Sand POC and Silt Content 221

5.5.4 Fabrics Cleaning/Washability 223

5.6 Discussion of Results 225

Page

6. THE LONGTERM FILTRATION PERFORMANCE OF THE SELECTED NWF. 228

6.1 Pilot Plant Modifications 229

6.2 Reservoir Water Source and Quality 230

6.3 Filter Media 231

6.4 General Conduct of Tests 237

6.4.1 Sampling Frequency and Analysis Methods 238

6.5 Discussion of Results 238

6.5.1 Hydraulic Performance 239

  6.5.1.1 Filter Run Time 239

  6.5.1.2 Filter Head Loss 240

6.5.2 Water Quality Improvements/Changes 245

  6.5.2.1 Temperature 245

  6.5.2.2 Turbidity 246

  6.5.2.3 Bacteriological Quality 246

6.5.3 Impurities Deposition Pattern 249

7. THE USE OF NWF TO PROTECT SSF TREATING CHEMICALLY PRE-TREATED WATER. 252

7.1 Pilot Plant Description 253

7.1.1 Pilot Plant Design 253

7.1.2 Installation and Time Schedule 256

7.1.3 Pilot Plant Flow Sheet 256

7.1.4 Filter Media 262

7.2 Raw Water Quality 263

7.3 General Conduct of the Experiments 266

7.4 Procedures and Analysis Methods 268

7.4.1 Operational Procedures 268

Page

7.4.2 Sampling 269

7.4.3 Methods of Analysis 270

7.5 Results 271

7.5.1 Hydraulic Performance 272

  7.5.1.1 Phase 1 272

  7.5.1.1.1 Filter Run Time 272

  7.5.1.1.2 Filter Head Loss 273

  7.5.1.2 Phase 2 276

  7.5.1.2.1 Filter Run Time 276

  7.5.1.2.2 Filter Head Loss 278

7.5.2 Water Quality Improvements/Changes 279

  7.5.2.1 Temperature 279

  7.5.2.2 pH 283

  7.5.2.3 Colour 283

  7.5.2.4 Turbidity 284

  7.5.2.5 Faecal Coliforms 287

  7.5.2.6 Particle Size Distribution 287

7.5.3 Filter Media Cleaning 290

7.5.4 Fabrics Washability 293

7.6 Discussion of Results 293

8. GENERAL DISCUSSION 296

8.1 Practical Considerations 306

8.2 Further Research 308

9. CONCLUSIONS 310

10. LIST OF REFERENCES 314

Page

11. APPENDICES 329

Appendix.1 Program listing TS1 for estimation of differential numbers from differential volumes. 330

Appendix.2 Procedure for determination of water POC and Chl-a, Sand profile POC, Chl-a and Dry Silt Content. 331

LIST OF TABLES

Table No.		Page
Chapter One		
1.1	Structural formulae of the repeating units of some common polymers.	44
1.2	Non-Woven fabric samples characterised	51
1.3	Previous experimental studies with NWF	54
1.4	Filter run times from Bridges	55
Chapter Three		
3.1	Fabrics subject to SEM analysis	86
3.2	Mean characteristics of mains water	104
3.3	Hydraulic conductivity of filter media	115
3.4	Filtration experiments filter media	123
3.5	Mean initial filter coefficient (m^{-1}), 0.3 m/h	134
3.6	Mean initial filter coefficient (m^{-1}), 1.0 m/h	135
Chapter Four		
4.1	NWF installed in the SSF units	159
4.2	Filter run times	174
4.3	Fabrics hydraulic conductivity	178
4.4	SSF filtrate turbidity	182
4.5	Presumptive total coliforms	186
4.6	Presumptive faecal Coliforms	186
4.7	POC and Chl-a removal	187
4.8	Total particle number / volume removal	187

Table No. Page

Chapter Five

5.1 NWF installed in the SSF units 205

5.2 Filter run times 208

5.3 Mean filtrate turbidity 214

5.4 Presumptive Coliforms 219

5.5 Presumptive faecal Coliforms 219

5.6 Mean bacteriological removal efficiency 220

5.7 POC and Chl-a removal efficiency 220

5.8 Mean particle removal efficiency 221

5.9 SSF sand profile POC and silt content 222

Chapter Six

6.1 Non-Woven fabrics properties 229

6.2 Filter media composition 234

6.3 Filter run times 239

6.4 Faecal Coliforms per 100 ml 248

6.5 Faecal Coliforms removal efficiency 249

Chapter Seven

7.1 NWF characteristics 262

7.2 Quality of river Thames at Egham main works intake. 266

7.3 Fabric specifications for the SSF 268

7.4 Phase 1 filter run times 273

7.5 Phase 2 filter run times 278

7.6 SSF filtrate turbidity 284

7.7 Mean faecal Coliforms removal 287

LIST OF FIGURES

Fig. No. | Page

Chapter One

1.1 The basic elements of a slow sand filter 29

1.2 Needle-punching process 46

1.3 A typical wet-bonding process 47

1.4 Dry-bonding process 47

1.5 Manufacture of spun-bonded NWF 48

1.6 NWF spun-lacing 48

Chapter Two

2.1 The porosity - specific surface relationship for some non-woven fabrics. 65

2.2 (a) Flow pattern around a cylinder at transitional regime. 70

(b) Flow pattern around two cylinders/fibres 70

2.3 Drag coefficient - Reynold's number correlation for flow around a cylinder and a bundle of tubes. 70

2.4 The correlation of C_d to Re for some NWF 72

2.5 Some dominant filtration phenomena in NWF 77

Chapter Three

3.1 The general view of the JXA -733 88

3.2 Console close-up (Column & X-ray spectrometer) 89

3.3 The SSF sand mean grading curve 98

3.4 The permeability/filtration column 101

3.5 Head loss pattern in lab. No. 27 108

3.6 Head loss pattern in lab. No. 28 108

Fig. No.		Page
3.7	Head loss pattern in lab. No. 45	109
3.8	Head loss pattern in SSF sand	109
3.9	Repeatability of hydraulic characteristics of lab. No. 45 .	110
3.10	Hydraulic characteristics of lab. No. 45	110
3.11	Hydraulic characteristics of lab No. 27	111
3.12	Hydraulic characteristics of lab. No. 28	111
3.13	Hydraulic characteristics of lab. No. 26	112
3.14	Hydraulic characteristics of lab. No. 44	112
3.15	Hydraulic characteristics of lab. No. 55	113
3.16	Hydraulic characteristics of lab. No. 80	113
3.17	Hydraulic characteristics of SSF sand	114
3.18	Theoretical & experimental relationship between the permeability factor and porosity of NWF.	117
3.19	NaCl - Conductivity calibration curve	122
3.20	4 % NaCl tracer test for the filtration column, at 0.3 m/h.	122
3.21	Kaolin particle size distribution (multiple-tube analysis), Log - Normal probability.	124
3.22	Kaolin cummulative particle size distribution, raw data.	127
3.23	Turbidity - Kaolin concentration calibration	127
3.24	Filtration experiments flow scheme	129
3.25	Initial filter coefficient, lab. No. 27, 0.3 m/h	136
3.26	Initial filter coefficient, lab. No. 25, 0.3 m/h	136
3.27	Initial filter coefficient, SSF sand, 0.3 m/h	137
3.28	Initial filter coefficient, lab. No.32, 0.3 m/h	137

Fig. No. Page

3.29 Initial filter coefficient, lab. No. 28, 0.3 m/h 138

3.30 Initial filter coefficient, lab. No. 26, 0.3 m/h 138

3.31 Initial filter coefficient, lab. No. 55, 0.3 m/h 139

3.32 Initial filter coefficient, lab. No. 44, 0.3 m/h 139

3.33 Initial filter coefficient, lab. No. 26, 1.0 m/h 140

3.34 Initial filter coefficient, lab. No. 25, 1.0 m/h 140

3.35 Initial filter coefficient, lab. No. 28, 1.0 m/h 141

3.36 Initial filter coefficient, lab. No. 27, 1.0 m/h 141

3.37 Initial filter coefficient, lab. No. 44, 1.0 m/h 142

3.38 Initial filter coefficient, lab. No. 55, 1.0 m/h 142

3.39 Initial filter coefficient, lab. No. 32, 1.0 m/h 143

3.40 Initial filter coefficient, SSF sand, 1.0 m/h 143

3.41 λ_o - S_o Relationship, 0.3 m/h 144

3.42 λ_o - S_o Relationship, 1.0 m/h 144

3.43 λ_o - d_p Relationship, 0.3 m/h, selected media 146

3.44 λ_o - d_p Relationship, 1.0 m/h, selected media 146

3.45 λ_o - d_p Relationship, 0.3 m/h 148

3.46 λ_o - d_p Relationship, 1.0 m/h 148

Chapter Four

4.1 The location plan of Ashford common pilot plant 152

4.2 Layout plan of the Ashford common pilot plant 154

4.3 Typical cross-section through a SSF unit 157

4.4 Ashford common SSF flow controller details 158

4.5 Mean monthly reservoir water POC 163

4.6 Mean monthly reservoir water Chl-a 163

Fig. No.		Page
4.7	Mean monthly microstrainer filtrate POC	165
4.8	Mean monthly microstrainer filtrate Chl-a	165
4.9	Inlet water POC	167
4.10	Inlet water Chlorophyll-a	167
4.11	Inlet water presumptive Coliforms	168
4.12	Inlet water presumptive *E. Coli*	168
4.13	Inlet water pH	169
4.14	Inlet water turbidity	169
4.15	AFM1 filter head loss (run 2)	176
4.16	AFM1 filter head loss (run 6)	176
4.17	AFM2 filter head loss (run 2)	177
4.18	AFM2 filter head loss (run 3)	177
4.19	AFM4 filter head loss (run 7)	179
4.20	AFM5 filter head loss (run 2)	179
4.21	AFM5 filter head loss (run 4)	180
4.22	Turbidity removal in SSF units	183
4.23	Presumptive Coliform counts	184
4.24	Presumptive *E. Coli* counts	184
4.25	Water POC removal in SSF units	185
4.26	Water Chl-a removal in SSF units	185
4.27	AFM2 POC variation in sand	189
4.28	AFM1 POC variation in sand	189
4.29	AFM4 POC variation in sand	190
4.30	AFM3 POC variation in sand	190
4.31	AFM2 Chlorophyll-a variation in sand	192
4.32	AFM1 Chlorophyll-a variation in sand	192

Fig. No. Page

4.33 AFM4 Chlorophyll-a variation in sand 193

4.34 AFM3 Chlorophyll-a variation in sand. 193

4.35 AFM2 silt content in sand 194

4.36 AFM1 silt content in sand 194

4.37 AFM4 silt content in sand 196

4.38 AFM3 silt content in sand 196

4.39 AFM5 silt content in sand 197

Chapter Five

5.1 AFM2 filter head loss (run 1) 210

5.2 AFM5 filter head loss (run 1) 210

5.3 AFM4 filter head loss (run 1) 211

5.4 AFM1 filter head loss (run 1) 211

5.5 AFM3 filter head loss (run 1) 213

5.6 Inlet water pH 213

5.7 Turbidity removal in SSF units 215

5.8 Presumptive Coliforms removal in SSF units 216

5.9 Presumptive *E. Coli* removal in SSF units 216

5.10 Water POC removal in SSF units 218

5.11 Water Chl-a removal in SSF units 218

Chapter Six

6.1 POC variation of inlet to main works SSF 232

6.2 Chl-a variation of inlet to main works SSF 232

6.3 Inlet water turbidity 233

6.4 Inlet water bacteriological quality 233

Fig. No.		Page
6.5	Cross-section through the suspended NWF multi-layer unit AFM1.	235
6.6	Cross-section through the suspended sand unit AFM5.	236
6.7	AFM5 filter head loss (last run)	241
6.8	AFM2 filter head loss (run 1)	243
6.9	AFM2 filter head loss (run 3)	243
6.10	AFM4 filter head loss (run 1)	244
6.11	AFM6 filter head loss (run 1)	244
6.12	Turbidity removal in SSF units	247

Chapter Seven

7.1	A typical cross section of a SSF unit	254
7.2	Plan and cross section of the clarifier	255
7.3	Egham pilot plant layout plan	257
7.4	Schematic hydraulic profile of Egham pilot plant	258
7.5	Raw water turbidity variation	264
7.6	Raw water pH variation	264
7.7	The average raw water particle size distribution, 400 μm tube.	265
7.8	S1 filter head loss (run 1), phase 1	274
7.9	S3 filter head loss (run 1), phase 1	274
7.10	S1 filter head loss (run 2), phase 1	275
7.11	S2 filter head loss (run 2), phase 1	275
7.12	S3 filter head loss (run 2), phase 1	277
7.13	S1 filter head loss (run 4), phase 1	277
7.14	S1 filter head loss (run 1), phase 2	280
7.15	S1 filter head loss (run 2), phase 2	280

Fig. No. Page

7.16 S2 filter head loss (run 1), phase 2 281

7.17 S2 filter head loss (run 2), phase 2 281

7.18 S3 filter head loss (run 1), phase 2 282

7.19 S3 filter head loss (run 2), phase 2 282

7.20 Apparent colour removal 285

7.21 Turbidity removal , phase 1 286

7.22 Turbidity removal , phase 2 286

7.23 Bacteriological quality improvement in the clarifiers. 288

7.24 Multiple-tube particle size distribution for the clarifier effluent. 291

LIST OF PLATES

Page

Chapter Three

Plate.1 Surface appearance of virgin lab. No. 26 90

Plate.2 Surface appearance of virgin lab. No. 27 90

Plate.3 Surface appearance of virgin lab. No. 28 91

Plate.4 Pore blinding due to calendering, lab.No.44 91

Plate.5 A close-up of virgin lab. No. 55 93

Plate.6 Cross section of virgin lab. No. 44 93

Plate.7 Cross section of virgin lab. No. 55 94

Plate.8 Cross section of virgin lab. No. 28 95

Plate.9 Close-up of virgin lab. No. 28 cross section 95

Plate.10 Blinding of used fabric lab. No. 55 96

Plate.11 Blinding of used fabric lab. No. 44 96

Plate.12 Cutting of non-woven fabrics with a dye 100

Plate.13 The permeability column 103

Plate.14 The set-up of permeability experiments 105

Plate.15 The filtration column 119

Plate.16 The set-up of filtration experiments 130

Plate.17 Model TA II Coulter counter with a sampling stand. 132

Chapter Four

Plate.18 Layout of the Ashford common pilot plant 155

Plate.19 Close-up of the slow sand filter units at the Ashford common pilot plant. 160

Page

Chapter Seven

Plate.20 The chemical mixing tank and PAC container at the Egham pilot plant. 260
Plate.21 A side view of the slow sand filter units at the Egham pilot plant. 261
Plate.22 A plan view of a fabric protected SSF unit after drainage of water, Egham pilot plant. 292

LIST OF PRINCIPAL SYMBOLS AND ABBREVIATIONS

(Other terms defined where quoted)

Symbols

A	An empirical correlation coefficient of the drag coefficient and the Reynold's number
a_F	Fibre radius
$A_F(\gamma)$	A dimensionless flow model parameter, a function of γ.
b	An empirical constant
c	Suspension number concentration
C_d	Drag coefficient
c_o	Initial suspension number concentration
d_f	Fibre diameter
d_p	Particle diameter
d_s	Filter grain diameter (sieve)
d_{10}	10 % passing diameter
d_{60}	60 % passing diameter
$\bar{d}$	The mean distance between the fibres
d'	Days
F	Total fibre length per unit area
F_d	Drag force
g	Gravitational constant of acceleration
h	Hour(s)
H_s	Head loss due to surface deposition
i	Hydraulic gradient
I	The average rate of collection of entrained particles per unit length of fibre.
k_e	Kinetic energy term
k_f	The turbulent coefficient of permeability

k_h	Happel's permeability factor
k_k	Kuwabara's permeability factor
k_q	Head loss coefficient
k_s	Initial head loss at the surface
k^1	Carman-Kozeny filter constant
K	Hydraulic conductivity
K_o, K_1	Bessel functions of zero and first order
l	litre
L	Depth of the filter /porous media
m	metre(s)
N	Number of rows of fibres
r	Radial coordinate
R	Correlation coefficient
Re	Reynold's number
s	second
S	clean media specific surface / specific surface area per unit volume.
S_c	Characteristic/projected area
S_o	Clean bed specific surface
v	Velocity of approach
v_b	Velocity in the bulk of the liquid
v_e	Effective velocity in the fabrics
v_s	Stokes velocity of the particle
w	Fabric weight per unit area
z	Nominal fabric thickness (unloaded)
Z	Total fabric thickness (unloaded)

Greek letters

α	Particle-fibre attachment efficiency
β	A dummy parameter for determination of pairs of $A_F(\gamma)$ and γ .
γ	Volume fraction of fibres in the fabric
ΔH	Filter bed head loss
ΔH_o	Clean bed filter head loss
ϵ	Filter media porosity
ϵ_o	Clean bed /filter media porosity
η	Overall single fibre collector transport efficiency
η_I	Efficiency due to interception mechanism
η_s	Efficiency due to sedimentation mechanism
θ	Angular coordinate
λ	Filter coefficient
λ_o	Initial/clean bed filter coefficient
μ	Kinematic viscocity
ν	Dynamic viscosity
ρ_b	Fabric bulk density
ρ_f	Fibre specific gravity
σ	Specific deposits / specific deposits per unit volume of filter media.
σ_u	Ultimate specific deposits
ϕ	Sphericity index
Ψ	Stream function

Abbreviations

cm	centimetre(s)
Chl-a	Chlorophyll-a

hrs.	hours
HRF	Horizontal Flow Roughing Filters/Filtration
JTU	Jackson's Turbidity Units
mg	milligrams
ml	millilitre(s)
mm	millimetre(s)
m mhos	milli - mhos = mhos x 10^{-3}
NTU	Nephelometric Turbidity Units
NWF	Non-Woven synthetic Fabric/(s)
PAC	Poly-Aluminium Chloride
PCA	Population Counting Accessory
POC	Particulate Organic Carbon
RSD	Relative Standard Deviation
SEM	Scanning Electron Microscope/Microscopy
SSF	Slow Sand Filter/Filtration
TOC	Total Organic Carbon
UOS	University of Surrey
U.V.	Ultra-Violet
VRF	Vertical Roughing Filter/Filtration
μg	microgram(s) = 1 x 10^{-6} grams
μm	micrometre(s) = 1 x 10^{-6} metres
μmhos	micro mhos = 1 x 10^{-6} mhos

Chapter One

1. INTRODUCTION

Slow Sand Filtration (SSF) is a unit operation in which raw or pre-treated water is filtered at a very slow rate (typically 2.8 to 11.1 x 10^{-5} m/s) through a fine granular medium (usually sand). In comparison to rapid sand filters which can be operated at filtration rates as high as 4.2 x 10^{-3} m/s (1,2), the rates applicable to Slow Sand Filters (SSF) can be justifiably regarded as slow. Literature (3) indicates that the first SSF to supply water (by carts) to a whole town was commissioned at Paisley, Scotland in 1804. In 1827, SSF designed by Robert Thom were used with little success at Greenock,Scotland. By 1829, James Simpson commissioned the first successful SSF at Chelsea water treatment works, London. The typical components of a modern SSF are shown on Fig. 1.1 . As regards the filter media characteristics, literature (4-6) suggests that the effective diameter (d_{10}) should be within the range of 0.15 - 0.35 mm and its uniformity coefficient (d_{60}/d_{10}) should be preferably less than 3. However, the validity of the proposed limits is still a subject for further research.

The basic transport and attachment mechanisms responsible for particle capture in rapid sand filters (7-10) contribute in a different pattern to the overall particle

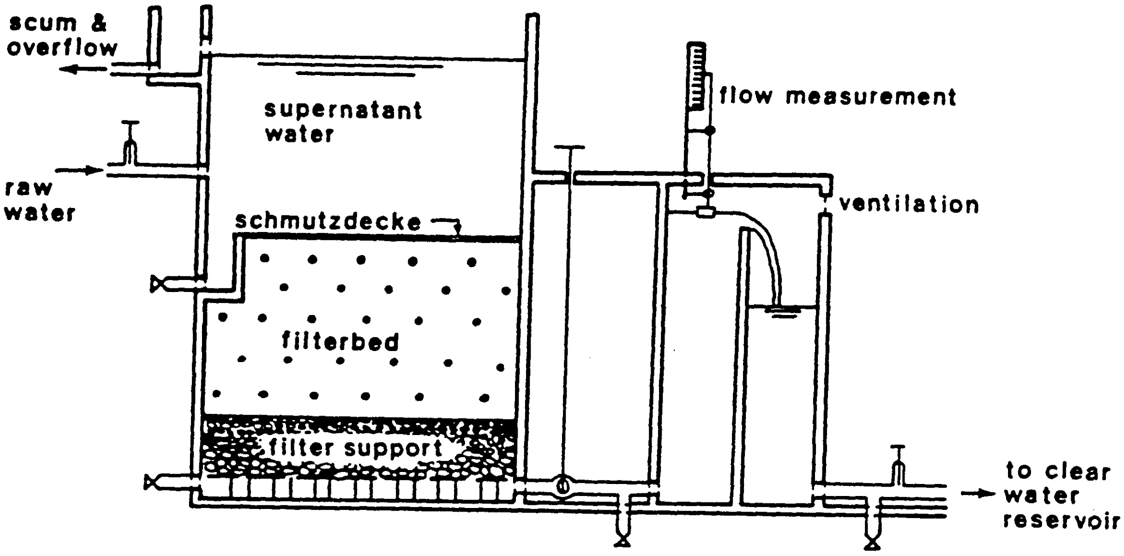


Fig. 1.1 The basic elements of a slow sand filter (after Van Dijk et al, (4)).

removal efficiency in SSF beds. This is primarily due to the "surface" nature of SSF caused by the smaller specific diameter of its grains and also the subsequent formation of the biological skin (schmutzdecke). The principal transport mechanisms by which impurities are brought into contact with the sand grains consist of straining, sedimentation, inertia, interception, diffusion and hydrodynamic forces. In general, the contribution of each mechanism varies depending on the raw water quality, filter media characteristics and the design rate of filtration.

The particle attachment occurring under favourable collector-particle surface conditions are dependent upon the chemical characteristics, electrical double layer interactions, Van der Waal's forces, adhesion and other biochemical related adsorption processes. Detachment mechanisms are unlikely to be of any significance in SSF beds because of the low filtration rates applicable and concentration of the majority of the treatment within the top layer of sand where biological adhesive forces are expected to be strong.

With regard to the overall treatment performance , SSF are superior than rapid sand filters especially in view of their exceptional ability to remove pathogenic bacteria (1,4,5) and viruses (11-14) . In addition, the prevalence of biochemical oxidation processes which play a major role in converting organic matter into harmless simple inorganic products discharged in the filtrate is another factor in favour of SSF . Although the majority of purification takes place within the top layer of sand, a substantial proportion of the biochemical and predatory removal processes takes place deeper in the sand bed (6,11) . Two distinct zones of purification in the SSF bed can be distinguished (15), these are the surface biological skin coating confined to the top few millimetres (10-20 mm) often referred to as the autotrophic zone and the heterotrophic zone which is estimated to extend some 300 mm deep. Historically, the most convincing proof of the effectiveness of SSF was demonstrated in 1892 when two neighbouring German cities drawing water from river Elbe were threatened with cholera outbreaks (1,15,16). While Altona escaped almost unscathed because its water was slow sand filtered, Hamburg was hit by a serious cholera epidemic. Besides all recent technological advances in the field of filtration of drinking water, at present SSF remains the most efficient individual filtration step in view of its ability to improve in one stage the physical, biological and chemical quality of water (17).

1.1 Theoretical Considerations

The fact that the filtration rate of SSF is so low that under normal circumstances laminar flow conditions prevail in the beds means that Darcy's law is applicable (18). In accordance with literature (19,20), it is possible to estimate the initial (clean bed) filtration efficiency of a SSF bed on the basis of established hypotheses . However, the prevalence of many biological processes which are not easy to comprehend and model presents problems with regard to modelling SSF beds . This is true because mathematical models are supposed to represent both the actual clarification processes and the corresponding pressure drop changes. Both of these have initial conditions in the absence of any biological processes. However, these are expected to change in a time - dependent manner which is not easy to predict when filters clog . Other general factors related to the inability to characterize the filter media, chemical nature of the suspensions and the physics of filtration accurately (21) make mathematical modelling of SSF beds a complex task.

A clean sand bed exhibits a resistance to flow which either can be experimentally determined from Darcy's law:

$$v = K . \Delta H_o / L \qquad \textbf{(1)}$$

or can be theoretically calculated from the Carman-Kozeny equation for porous media:

$$\frac{\Delta H_o}{L} = \frac{k^1 \nu S_o^2 v}{g \epsilon_o^3} \qquad \textbf{(2)}$$

Where, ΔH_o = Clean bed head loss, L = Depth of porous media, K = Hydraulic conductivity, k^1 = Carman-Kozeny filter constant, v = Approach velocity, ν = Kinematic viscosity, ϵ_o = Clean bed porosity, S_o = Clean bed specific surface area per unit volume and g = Gravitational constant of acceleration.

The theoretical determination of clean bed headloss presents no major problems as long as the parameters S_o and ϵ_o can be obtained or estimated accurately. However, since the filter bed head loss is a function of corresponding changes in specific surface (S) and porosity (ϵ) modified by deposited materials, to predict any future head loss correctly one must resort to the use of mathematical models (10) which would be expected to quantify the changes in the filter bed at any time.

For spherical granular media, an average Carman-Kozeny filter constant k^1 of 5.0 is commonly adopted (8,10). Considering the clean bed case and combining equations **(1)** and **(2)**, the theoretical hydraulic conductivity can be expressed as :

$$K = (g \epsilon_o^3)/(k^1 \nu S_o^2) \qquad \textbf{(3)}$$

Considering filtration, upon assuming that the filter pores are uniform in a statistical sense in all parts of the granular filter bed depth and also that the probability of particles being retained anywhere in the bed is the same, a filter coefficient (λ) can be defined such that the removal of a suspension (C) with respect to bed depth (L) in the filter is a first order equation :

$$-\frac{\partial C}{\partial L} = \lambda C \qquad \textbf{(4)}$$

A further assumption for validity of equation **(4)** is that in every layer, the suspension entering and leaving it is uniformly dispersed. Integration of equation **(4)** at the commencement of filtration when the elapsed filtration time t = 0 yields :

$$C = C_0 e^{-\lambda L} \qquad (5)$$

It is accepted in principle (7) that the build up of specific deposits (σ) within the filter pores makes the filter coefficient (λ) dependent on λ_0 and the specific deposit changes such that $\lambda = f(\lambda_0 , \sigma)$ in a manner which for SSF beds is not easy to predict and also because the exponential decline of equation **(5)** becomes no longer valid.

On the basis of the balance of inlet suspension and materials deposited in the filter media pores and upon neglecting the effects of diffusional gradients, a general mass balance equation which takes the form of equation **(6)** can be defined (10,19):

$$-\frac{\partial C}{\partial L} = \frac{1}{v}\frac{\partial \sigma}{\partial t} + \frac{(\epsilon_0 - \sigma)}{v}\frac{\partial C}{\partial t} \qquad (6)$$

Since the rate of change of concentration (vol./vol.) of most dilute suspensions met in drinking water treatment is negligible, the term $\partial C/ \partial t$ is neglected thus reducing equation **(6)** to:

$$- \frac{\partial c}{\partial L} = \frac{1}{v} \frac{\partial \sigma}{\partial t} \qquad (7)$$

The mass balance equation **(7)** originally proposed by Iwasaki (20) for SSF is largely valid for filtration systems handling inorganic pollution with negligible biological activities involving living organisms. Otherwise its validity is only limited to filtration times during which multiplication of bacteria (or other micro-organisms) is negligible. One must not forget the fact that multiplication of living organisms goes side by side with creation of new matter and death. Until such a time when accurate representative growth and death curves of all dominant organisms resident in SSF beds at any time can be obtained, attempts to produce acceptable mathematical models of SSF beds will be of very limited use. It should also be noted that development of such models for mixed cultures presents considerable problems from a microbiological point of view, even discounting the complexities of considering motile species .

The correlation of filter coefficient (λ) and specific deposits (σ) is known to have been a subject of much disputes amongst workers in the field of mathematical modelling of rapid sand filters (21). With the knowledge that rapid filtration involves almost negligible biological activities, this observation simply points out the possible extent of differences in opinions which can be expected when attempting to model SSF .

1.2 Slow Sand Filtration Applications

In Europe, with the exception of France, slow sand filtration was widely applied in the treatment of urban water supply schemes by 1890 (3) . However, it was soon realized that they could not cope with high inlet water turbidities. By the early 1900's most SSF were provided with sedimentation units for pretreatment or long-term storage reservoirs which also facilitated settling (22). However, the invention and subsequent development of rapid sand filtration in the 1880's in the USA (3) generally discouraged the use of SSF in new water works to the extent that within a few years the use of rapid sand filters became almost universal there. In Europe, by 1920's most urban water treatment works changed the pattern of use of SSF to secondary filtration by introducing rapid sand filters as a primary filtration step (23). Incidentally, at present nearly all the large urban water treatment plants using SSF at least apply the principle of double sand filtration. However, by 1950's the decline in popularity of slow sand filters in favour of rapid sand filters in Europe was very apparent (24).

Today the treatment potential of slow sand filtration is demonstrated by the fact that many cities in Europe (e.g. Paris, Zurich, Amsterdam, Antwerp and London metropolitan) still use it as a secondary filtration step preceded by either rapid sand filters or microstrainers. Even in the USA, SSF have continued to be successfuly used in small scale water supply schemes serving rural communities (2). In fact, in these small communities, there has even been a significant construction of new SSF units during the last three decades (25). The recent resurgence of interest to carry out research work on SSF in the USA (25-32) is an encouraging development. In the UK, it is estimated that at present between 20 - 25 % of potable water is treated by SSF (22,33,34) either as a secondary or as the main filtration process in small water works. In the Thames Water Authority Region more than 70 % of water treatment capacity utilizes SSF as a secondary filtration stage (33).

Literature (13,14,35-38) describes experience in the use of SSF within the Thames Water Authority (formerly The Metropolitan Water Board) especially in relation to bacterial and virus removal over a long period. The use of SSF in developing countries is also well documented (1,4-6,11,39-52). In these countries, the use of SSF is considered to be particularly suitable for rural water supply schemes in view of the ease and simplicity of operation and maintenance. However, often problems related to lack of community participation and proper training of operators are common (5,39,53). In some cases, inappropriate design of filter control devices has been reported to have brought operational difficulties (40).

1.2.1 Operational limitations of SSF

The main factor which limits applicability of SSF is its inability to handle directly raw water with very high turbidity especially of inorganic origin. If no or insufficient pretreatment of raw water is undertaken, the outcome is very short filter run times which place a big demand in terms of labour and effort in filter cleaning even if the process is mechanized. In some instances SSF units are reported to have been by-passed by plant operators in order to avert the cleaning work load (39,40).

Although there are a lot of beneficial factors in favour of algal activities in SSF beds (1,11,54) , massive die off of algal blooms or proliferation of blocking type of algae like Nitzschia acicularis, Asterionella formosa, Anabaena, Stephanodiscus hantzschii and Stephanodiscuss astraea is undesirable because they can block the filter very fast (23). If such a proliferation is accompanied with the existence of blanket weeds like Melosira varians, Cladophora and Spirogyra, considerable labour is required to remove them prior to skimming the sand. The influence of algae on SSF operation can at times be so dramatic that filter run lengths as short as 12 days are recorded (55) . For example as a result of these types of operational problems, in Thames Water Authority, up to 70 % of direct operational costs for SSF are associated with filter cleaning and resanding (33).

1.2.2 Attempts to offset operational limitations of SSF

The main objectives of attempts geared towards this goal are two fold. The first is to reduce the total load of impurities going directly into the sand bed by some form of pretreatment which would in turn increase the filter run times thus reducing the costs and frequency of cleaning the SSF beds. The second is to simplify the cleaning operations of the sand beds. The use of longterm storage and/or sedimentation prior to SSF as a pretreatment to reduce mainly the inorganic load has already been mentioned. Another somewhat similar approach involves the use of the double sand filtration technique with rapid filters (or microstrainers) as primary filtration units (23). The use of in-situ hydraulic cleaning with a system of lances was previously attempted with little success in Europe (35,56-58). Trials to shade SSF units with plastic covers to reduce intensity of algae activities were abandoned due to difficulties related to handling the covers (14).

The earliest recorded use of Horizontal flow Roughing Filters (HRF) as pretreatment for SSF dates back in 1804 (3) when John Gibb installed the first SSF with roughing filters to supply an entire city at Paisley, Scotland. More recent applications of HRF as a means of reducing both the organic and inorganic loads of SSF have been reported

(39,52,59-61). Preliminary investigative and field work in the use of Vertical Roughing Filters (VRF) for small scale rural water supplies have been reported (50,51). Studies on the potential of using Non-Woven synthetic Fabrics (NWF) to protect SSF beds were initiated at Imperial college in collaboration with the University of Surrey in 1982 (62). A follow up field work was carried out in 1985 (63) prior to the present work. Since then NWF have been satisfactorily used in small scale plants in Somalia and Peru (42,50). In 1987, a new research study in the potential of using a conventional suction dredger to clean the SSF sand in situ was initiated by Thames Water Authority at Ashford Common Water Treatment Works. Although so far this work is still in progress (64), it is likely that the costs of acquisition of such a dredger and the corresponding sand cleaning system will be prohibitive for small scale water treatment systems.

Amongst the potential untried methods discussed here, the only one which would be likely to meet the stated objectives at a relatively low capital costs if proven to be performing well would be the use of NWF . It is postulated that the combination of high specific surface area and higher porosity of NWF would be expected to reduce the rate of head loss and also concentrate the majority of purification (autotrophic zone) in its depth. To do so economically, installation of only a small number of layers of NWF on top of sand would be necessary. The sand bed would be expected to serve as a polishing layer in addition to acting as a second barrier against edge penetrations. In ideal circumstances, the routine maintenance of the SSF would be reduced to cleaning the NWF only. Therefore this study will concentrate on investigating the efficacy of protection of SSF beds with NWF. In the next sub-chapter, fundamental properties of synthetic fabrics are introduced.

1.3 Synthetic Fabrics Chemistry and Classifications

The use of synthetic fabrics in water filtration will eradicate the difficulties in using fabrics made from natural fibres experienced during the 18th and 19th centuries (3,46,65). Previously, the use of these fibres was discontinued because their decomposition products tainted water. Therefore, the discovery of polymer chemistry in 1930's and the subsequent commercial production of synthetic fabrics between mid 1930's and 1940's (66-68) marked a new era which has led to the revival of interest in the use of fabric filters in drinking water filtration.

1.3.1 Synthetic Fabrics Chemistry

Synthetic fabrics consist of polymers of organic compounds made up of long, chain-like molecules with repeating molecular units linked by covalent bonds. A single molecular chain commonly contains a thousand or more repeating units which can reach a total length in excess of 1 μm (69). The atoms which form the back bone of organic polymers are predominantly Carbon and Hydrogen, sometimes in combination with Oxygen or Nitrogen. Different polymers have different repeating units which are responsible for differences in chemical behaviours of the fibres or yarns and hence the fabrics.

The process of Polymerisation in which small molecules of the monomer undergo reaction to form long chains may proceed in a variety of ways (70). These can be divided into two principal categories, Addition and Condensation polymerization which have major structural implications for the final product .

1.3.1.1 Addition polymerisation - This is a process in which monomer molecules link together without elimination of atoms to form by-product molecules. Poly-Vinyl Chloride is produced in this way:

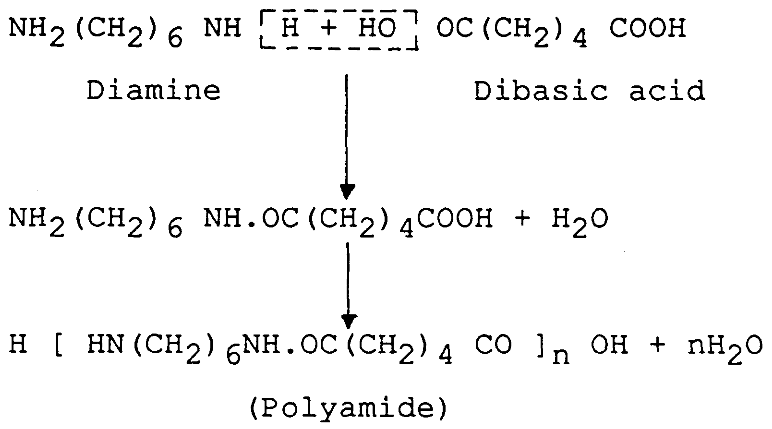
$$CH_2{=}CHCl + CH_2{=}CHCl + CH_2{=}CHCl \quad \text{(Vinyl Chloride)}$$

$$\downarrow$$

$$-CH_2-CHCl-CH_2-CHCl-CH_2-CHCl- \quad \text{(Poly-Vinyl-Chloride)}$$

Other examples of addition polymers are Polypropylene, Polyethylene and Polystyrene.

1.3.1.2 Condensation polymerisation - This is a process in which the linkage of monomer molecules takes place by action which results in the elimination of a by-product molecule, commonly water. Polyamides are produced in this way:



$$NH_2(CH_2)_6\ NH\ \boxed{H + HO}\ OC(CH_2)_4\ COOH$$

$$\downarrow$$

$$NH_2(CH_2)_6\ NH.OC(CH_2)_4COOH + H_2O$$

$$\downarrow$$

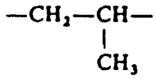
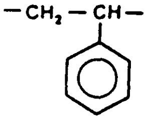
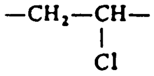
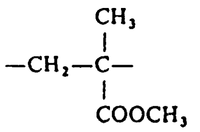
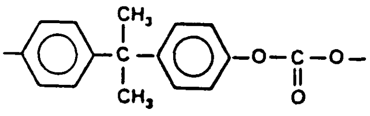
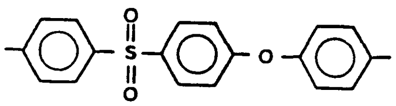
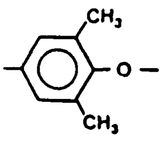
$$H\ [\ HN(CH_2)_6NH.OC(CH_2)_4\ CO\ ]_n\ OH + nH_2O$$

Some common condensation polymers include Polyesters, Polycarbonates and Polyether sulphonates. Table 1.1 gives the repeating units of some polymers.

1.3.2 Synthetic Fabrics Classification

The term synthetic fabrics refers to man-made textiles in the sense that components which form the textile (i.e. fibres, webs or yarns) are produced artificially in contrast to, say cotton whose fibres are produced by natural processes. In general, synthetic fabrics can be subdivided into three groups; Woven, Non-Woven and Composites :

Table 1.1 Structural formulae of the repeating units of some common polymers, modified after Dyson *et al*, (71).

Polymer	Structural repeat unit	Stiffening agent
Polyethylene	$-CH_2-CH_2-$	-
Polypropylene	 $-CH_2-CH(CH_3)-$	$-CH_3$ side group
Polystyrene		Phenyl ring side group
Polyvinylchloride	 $-CH_2-CH(Cl)-$	Polar side group
Polymethylmethacrylate	 $-CH_2-C(CH_3)(COOCH_3)-$	Di-substituted carbon
Polycarbonate		Benzene rings in chain
Polyethsulphone		Benzene rings in chain
Polyphenylene oxide		Substituted benzene ring in chain

1.3.2.1 Woven fabrics - These include all fabrics made from yarns which in turn consist of several fibres. The yarns can be invariably produced as continuous filaments, monofilaments or multi-filament yarns. All fabrics processed by weaving or knitting fall into this group. There are a few other types of fabrics which are made by a combination of sewing and knitting which are regarded to be woven.

1.3.2.2 Non-Woven fabrics - These include all the fabrics which are manufactured directly from fibres or webs without the need to produce yarns. They are usually said to be produced by fibre-bonding (72,73). Non-Woven fabrics with fibres oriented in one direction only can be given additional structural integrity by; thermal or chemically induced fibre fusion, needle-felting or application of adhesives or resins on the surface.

1.3.2.3 Composites - This is a small group of fabrics made up of a combination of both woven and non-woven elements. One example of a composite fabric is the needle-weave in which the fleece staple is needled onto a woven fabric.

Since the majority of woven fabrics made from tapes or monofilament yarns are very thin (usually less than 1.0

mm), they were not considered appropriate for application with SSF. This is because such thin fabrics would not be expected to provide enough storage space for particles captured during the extended filter run times. Moreover, the dominant capture mechanism would probably be only of surface nature in place of including additional capture within the fabrics depth. The same is true for most composites.

1.4 Non - Woven synthetic Fabrics (NWF)

1.4.1 NWF Manufacture

Five methods of production of NWF are identified (67,70,73,75), these are:

1.4.1.1 Needle-felting/punching - In this process, a needle-loom with a set of barbed hooks is repeatedly punched through fibre webs laid by carding or garnetting. These needles cause fibres to become entangled tightly together in a three dimensional network. Often a scrim is placed in between the fibre webs to provide extra strength to the fabric.

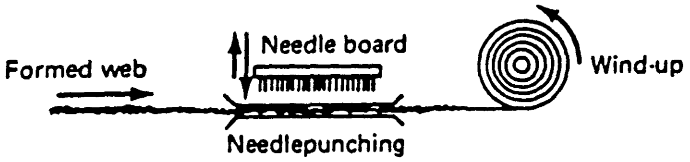


Fig. 1.2 Needle - Punching Process

1.4.1.2 Wet-bonded - Production involves water extraction, drying and rolling of a dispersion of synthetic fibre staples in water. Binders are/can be added at a convenient stage of production. This technique is suitable for short fibres or those with very low surface friction.

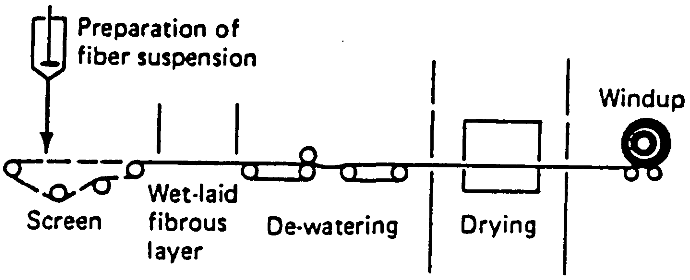


Fig. 1.3 A Typical Wet-Bonding Process.

1.4.1.3 Dry-bonded - Compressed sheets of fibre are carded (smoothened out) and garnetted by rollers or air-laid to form webs. The layer(s) of fibres are joined and compressed into a fabric that holds fibres together by applying an adhesive or binders like a resin or the application of heat .

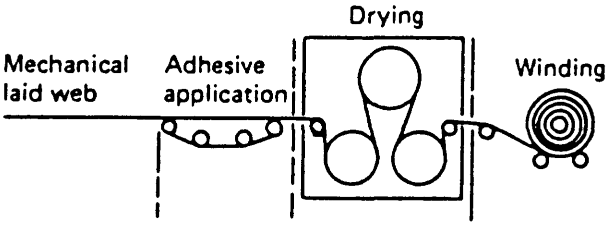


Fig. 1.4 Dry -Bonding Process.

1.4.1.4 Spun-bonded - In this case, after extrusion from a spinneret, fibres are oriented over a conveyer prior to fusing the web by heat, pressure or chemical activation. Essentially this method combines melting and spinning of the fibres. This process also allows fusing of two different types of fibres.

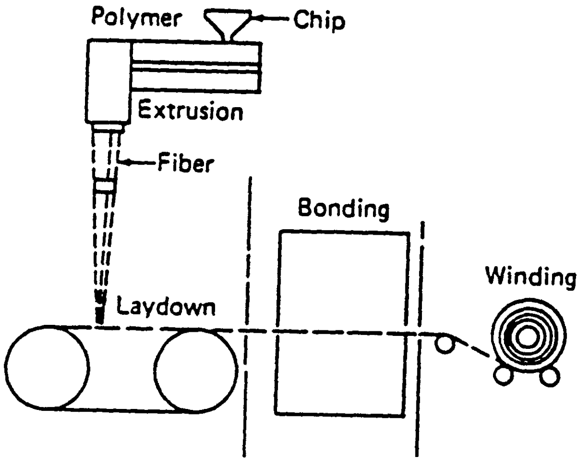


Fig. 1.5 Manufacture of Spun-bonded NWF.

1.4.1.5 Spun-lacing - Here jets of water are employed to entangle fibres and hold them together by friction only without fusion or application of any adhesives.

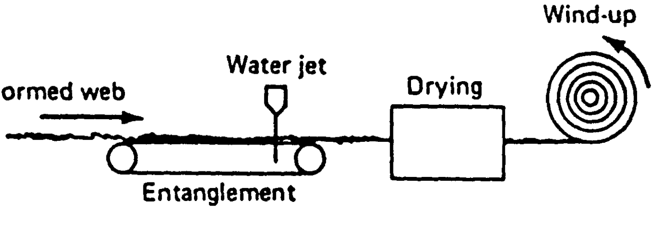


Fig. 1.6 NWF Spun - lacing.

The complexity of the different production processes means that besides the sophistication of quality control measures taken during production, some local variations of physical properties of fibres/fabrics prevail. Experience shows that even the diameter of a short single fibre staple is characterised by some local variations (76). Local variations of fabric thickness, pores, intertangling or even bonding are not unusual. This means that any characterization of the fabric geometric properties evaluated by calculations based on physical properties must be regarded as average rather than a perfect characteristic. In practice, interpretation of physical, chemical and mechanical properties of NWF vary largely due to the non-existence of standard testing procedures (72,73). Nevertheless, reviews of general properties of fabrics/fibres have been given (76-79).

Literature (79) suggests that in the commercial market, Polypropylene dominates the non-woven synthetic fabrics field. Some of the most common advantages of using Polypropylene fibres are listed below (68,70,80) :

- High abrasion resistance when wet or dry.
- Blends well with other fibres during production.
- Since it is free from polar groups (like Amides in Nylon and Esters in Polyester) it has a good fibre stain resistance and hence should be easier to clean when dirty.

-Has an excellent resistance to most chemicals, alkalis, acids and oxidizing agents met in drinking water treatment.

-Has sufficient resistance to fungus and organic acids.

-Has reasonably high resistance to dry heat or Ultra Violet light degradation when stabilized.

-Has an excellent fatigue resistance.

For cases where fibres are bonded with binders, the stability and resistance of the binder upon exposure to adverse conditions is critical in NWF selection (77). In almost all cases, the mechanical strength of the fabric is an important factor in relation to handling during washing.

1.4.2 NWF Characterization

A survey of NWF commercially available in the UK market was carried out in 1986. During this exercise, data on the physical and chemical properties of the fibres and fabrics was obtained from the manufacturers. With this data, laboratory measurement of some fabric properties like thickness and weight supplemented with information from published literature, the fabrics were characterized as indicated in table 1.2 .

At the request of the manufacturers, the fabrics were identified by laboratory numbers in place of their trade

Table 1.2 NON-WOVEN FABRIC SAMPLES CHARACTERISED.

SUPPLIER NUMBER	LAB. NUMBER	FIBRE POLYMER COMPOSITION	PRODUCTION TECHNIQUE	(d_1) APPR. FIBRE DIAMETER (μm)	(z) AVR. FABRIC THICKNESS (mm)	$[\rho_f]$ FIBRE SPEC. GRAVITY	$[\rho_b]$ AVR. FABRIC BULK DENSITY (g/cm^3)	$[1 - \rho_b/\rho_f]$ CALCULATED POROSITY (%)	[A] SPEC. SURF. AREA PER SQ. MTR. (m^2)	[S] SPEC. SURFACE AREA PER CU. MTR. (m^2)	1985 PRICE PER SQ. MTR. FABRIC (p)	1985 PRICE PER CU.MTR. FAB. (£)
1	11	PE	NF - SB	27.3	1.5^{-}	1.38	0.100	93	15.93	10, 620	-	-
	12	PE	NF - SB	27.3	1.9^{-}	1.38	0.111	92	22.30	11, 737	-	-
	13	PE	NF - SB	27.3	2.3^{-}	1.38	0.117	92	28.67	12, 465	-	-
	14	PE	NF - SB	27.3	2.8^{-}	1.38	0.121	91	36.10	12, 893	-	-
	15	PE	NF - SB	27.3	4.4^{-}	1.38	0.125	91	58.40	13, 273	-	-
2	21	PP	NF - CT	29	4.4^{**}	0.91	0.070	93	27.6	10, 568	120	462
	22	PP	NF - CT	33	4.4^{*}	0.91	0.087	90	51.2	11, 625	140	318
	23	PP	NF - CT	33	4.4^{*}	0.91	0.080	91	46.8	10, 626	135	307
	24	PP	NF - CT	33	4.4^{*}	0.91	0.106	88	61.9	14, 077	150	341
	25	PP	NF - CT	48	4.1^{*}	0.91	0.116	87	43.4	10, 609	200	488
	26	PP	NF - CT	48/100	6.0^{**}	0.91	0.182	80	74.8	10, 833	350	583
	27	PP	NF - CT	33	3.6^{**}	0.91	0.108	88	51.95	14, 431	150	417
	28	PP	NF- CT	33	4.8^{**}	0.91	0.100	89	63.4	13,266	150	313
3	31	PE/PVC	RSPB$^{(x)}$	50/40	9.0	1.38/1.392	0.0178	99	9.9	1, 100	240	267
	32	PE/PVC/PA	RSPB$^{(x)}$	50/40/40	13.0	1.38/1.39/1.14	0.0257	98	23.4	1, 671	520	372
	33	PE/PVC	RSPB$^{(x)}$	50/40	20.0	1.38/1.392	0.026	98	22.3	1, 115	630	315
4	41	PP	NF - TB	27.9	0.6	0.91	0.167	82	15.76	26, 267	35	583
	42	PP	NF - TB	27.9/30.5	0.95	0.91	0.147	84	23.92	25, 179	39	411
	43	PP	NF - TB	27.9/30.5/41.4	1.2	0.91	0.192	79	31.66	26, 381	58	483
	44	PP	NF - TB	27.9/30.5/41.4	1.3	0.91	0.231	75	43.21	33, 238	76	585
	45	PP	NF	27.9/30.5/41.4	3.2	0.91	0.094	90	43.21	13, 504	85	266
5	51	PP/PET	TB	40	0.4^{+}	0.90/0.92	0.175	81	6.2	15, 500	29.9	748
	52	PP/PET	TB	40	0.5^{+}	0.90/0.92	0.200	78	8.8	17, 600	35.3	706
	53	PP/PET	TB	40	0.7^{+}	0.90/0.92	0.200	78	12.4	17, 714	39.8	587
	54	PP/PET	TB	40	0.8^{+}	0.90/0.92	0.238	74	16.8	21, 000	< 100	<1250
	55	PP/PET	TB	40	1.0^{+}	0.90/0.92	0.230	75	20.3	20, 300	70.7	707

Table 1.2 <u>NON-WOVEN FABRIC SAMPLES CHARACTERISED</u> (Contd.)

SUPPLIER NUMBER	LAB. NUMBER	FIBRE POLYMER COMPOSITION	PRODUCTION TECHNIQUE	(d_f) APPR. FIBRE DIAMETER (μm)	(z) AVR. FABRIC THICKNESS (mm)	$[\rho_f]$ FIBRE SPEC. GRAVITY	$[\rho_b]$ AVR. FABRIC BULK DENSITY (g/cm^3)	$[1 - \rho_b/\rho_f]$ CALCULATED POROSITY (%)	[A] SPEC. SURF. AREA PER SQ. MTR. (m^2)	[S] SPEC. SURFACE AREA PER CU. MTR. (m^2)	1985 PRICE PER SQ. METRE FABRIC (p)	1985 PRICE PER CU.MTR. FAB. (£)
5	56	PP/PET	TB	40	1.2^+	0.90/0.92	0.233	74	24.7	20, 583	< 100	<1250
	57	PE	NF	30	1.5^+	1.38	0.140	90	20.3	13, 533	52	347
	58	PE	NF	30	2.0^+	1.38	0.145	90	28.0	14, 000	67	335
	59	PE	NF	30	2.5^+	1.38	0.140	90	33.8	13, 520	96	384
6	61	PE/PVA	RSPB(CB)	39.6	15.0	1.38/1.19	0.0387	97	38.17	2, 545	280	187
	62	PP/PE	TB	21.6/17.6	7.0	0.91/1.38	0.0286	98	36.83	5, 261	530	737
7	71	PP	SB	55.5/39.2	0.36^+	0.91	0.189	79	6.1	16, 944	21	583
	72	PP	SB	- do -	0.40^+	0.91	0.225	75	8.1	20, 250	26	650
	73	PP	SB	55.5/39.2	0.45^+	0.91	0.249	73	10.1	22, 444	31.5	700
	74	PP	SB	- do -	0.48^+	0.91	0.283	69	12.3	25, 625	35.5	740
	75	PP	SB	55.5/39.2	0.49^+	0.91	0.306	66	13.5	27, 551	43.5	887
	76	PP	SB	- do -	0.53^+	0.91	0.321	65	15.3	28, 868	-	-
	77	PP	SB	55.5/39.2	0.56^+	0.91	0.339	63	17.1	30, 536	51.5	920
	78	PP	SB	- do -	0.63^+	0.91	0.365	60	20.7	32, 857	55.0	873
	79	PP	SB	55.5/39.2	0.71^+	0.91	0.394	57	25.3	35, 634	70.0	986
	80	PP	SB	- do -	0.72^+	0.91	0.403	56	26.1	36, 250	74.0	1028

<u>**LEGEND:**</u>

PP = Polypropylene
PA = Polyamide
PE = Polyester
PET= Polyethylene
PVA= Poly-Vinyl-Acetate
PVDC=Poly-Vinyldine-Chloride
PVC = Poly-Vinyl-Chloride

RSPB= Resin spray-bonded
NF-CT = Needle-felted on carrier thread
NF = Needle - felted
SB = Spun - bonded
RB = Resin bonded
TB = Thermic bonded
(x)= Acrylate PVDC binder

* = By dial gauge
** = Measured at IC Laboratory.
+ = At 2.0 KN/m^2 load
- = At 5.0 KN/m^2 load
p = Pence
$S = (A/z)$ m^2/m^3

names. Although the list in table 1.2 by no means exhausts all NWF available in the UK market, it is representative of the range found in Europe at large . In order to get a better insight into the morphology of the fabrics, scanning electron microscopy of a selected number of virgin fabric samples later used for filterability investigations was carried out.

1.5 Previous Research Studies

Experimental studies of the perfomance of SSF units with NWF layers have been carried out within the last few years and mainly by research groups at Imperial College, London and the University of Surrey (Table 1.3). Until the work of Bridges (63) began to compare directly the performance of different types of fabrics, the choice of fabric for study had been largely empirical. Moreover,two types of fabrics have been made integral components in two operational package SSF systems without a full comparative assessment of alternative materials and multi-layer configurations being carried out.

1.5.1 Filter run times

Three separate studies have carried out experimental trials of a SSF with a fabric layer in parallel with a reference filter without any fabric. Wheeler et al(81) considered the performance of two layers (26 mm total thickness) of a high porosity material (98%) and found that the average

Table 1.3 Previous Experimental Studies with NWF

Reference	Date	Fabric details	SSF Size (m^2)
Liversidge(62)	1982	One layer,Z=13,S=1671 ϵ=98,PE/PVC/PA-RSPB	28.3
Wheeler et al (81)	1982/3	(i)Two layers,Z=26,S=1671 ϵ=98,PE/PVC/PA-RSPB	0.8/1.5
		(ii)Six layers,Z=90,S=2545 ϵ=97,PE/PVA-RSPB	1.5
Rodman <u>et al</u> (82)	1984	One layer,Z=15, S= 2545 ϵ=97 , PE/PVA - RSPB	2.0
Wheeler (84)	1984/5	Three layers,Z=45,S=2545 ϵ=97, PE/PVA-RSPB	1.5
Graham (42)	1985	One layer,Z =13, S=1671 ϵ=98, PE/PVC/PA -RSPB	28.3
Bridges(63)	1985	(i)One layer,Z=13,S=1671 ϵ=98, PE/PVC/PA-RSPB	1.5
		(ii)One layer,Z=0.5,S=17600 ϵ=78, PP/PET -TB	1.5
		(iii)One layer,Z=.95,S=25179 ϵ=84, PP - NF/TB	1.5
		(iv)One layer,Z=4.5,S=10609 ϵ=87, PP-NF/CT	1.5
		(v)One layer,Z=8,S=10615 ϵ=82, PP - NF/CT	1.5

Legend:

Z = Total fabric thickness (mm)

S = Specific surface (m^2/m^3)

ϵ = Fabric porosity (%)

PP= Polypropylene
PE= Polyester
PVC= Poly-Vinyl-Chloride
PA= Polyamide
PVA= Poly-Vinyl-Acetate
PET= Polyethylene
NF = Needle-Felted
TB = Thermic Bonded
CT = Carrier Thread
RSPB = Resin Spray Bonded

filter run time was 16.7 days as compared to 5.2 days for the reference filter. This represented an improvement factor of 3.2 . Rodman et al (82) also considered a high porosity fabric (97%) and found that a single layer (15 mm thick) increased the average filter run time by a factor of 2.0 when compared to the reference filter. Bridges (63) made a preliminary, parallel study of five different single layer fabrics, his results are shown in table 1.4 . Again the results indicate that for the three fabrics with significant thickness (> 4 mm) an increased filter run length can be achieved by the presence of a fabric layer. In all three studies, the filtration rate was in the range of 0.24 to 0.34 m/h .

Table 1.4 Filter Run Times From Bridges (63)

Fabric	Porosity (%)	Nominal thickness (mm)	Filter run time (days) Run 1	Run 2
Reference	-	-	10.2	7.0
1	78	0.5	8.8	6.9
2	84	0.95	8.6	7.0
3	87	4.5	11.0	8.0
4	82	8.0	14.2	9.6
5	98	14.0	11.4	10.6

1.5.2 Silt Retention

The principal objective in using a fabric layer is to move the location of the purification process into the fabric instead of the top sand layer. Consequently, the fabric filtration properties must be such that particle penetration through the fabric and into the sand must be minimized. In each of the experiments summarized in table 1.3, silt penetration through the fabric and into the sand was observed and generally it was the head loss resulting from particle deposition in the sand that terminated each filter run. Rodman et al (82) reported that at the end of each filter run, the same extent of material penetration into the sand had occurred for the filter with fabric and the reference filter. The penetration of particles is not surprising since,with the exception of the study by Bridges (63), all previous studies employed high porosity, low specific surface fabrics that would be expected to have a low particle capture efficiency.

Wheeler et al(81) measured the amounts of solids deposited (silt) in two layers of fabric and in the top 2 cm of sand of an experimental SSF and found that approximately 44 % by volume of the total solids retained had penetrated the fabrics and was deposited in the top sand layer. In a later work, with six layers of high porosity fabric (90 mm total thickness), Wheeler et al(83) showed that over 80 % of solids retained in the multilayer fabric were retained in the top layer alone and 99 % in the top two layers. In the same experiment Wheeler et al also reported a similar degree of solids penetration into the sand (47 % of total silt extracted from fabric and top 5 cm of sand).

Notwithstanding the appreciable amounts of solids accumulated within the fabrics during filtration, both Wheeler et al (81) and Bridges (63) reported negligible head loss across the fabrics at the end of each filter run.

1.5.3 Filtrate Water Quality

Rodman et al (82) reported that over a three month period of filter testing there was no significant difference in overall treatment performance between the fabric protected filter and the reference. With regard to filtrate water quality, Bridges (63) also reported identical reductions in turbidity for his reference filter and the five parallel filters with fabrics. Overall bacterial removals (On the basis of Presumptive *Escherichia coli* and 37°C/48 h plate counts) during the two filter runs were similarly equivalent in Bridges' study although influent concentrations were reported to have been relatively low. Recent work by Wheeler (84) has demonstrated significant micro-biological purification by three layers (45 mm total thickness) of high porosity fabric placed on an experimental SSF. Using faecal bacteria and bacteriophage as indicator organisms Wheeler was able to follow their removal with depth through the fabric and sand layers.

1.5.4 Fabric Biology

The existence of biological populations within mature SSF is widely understood but only a small amount of information exists on the detailed nature of these populations and their behaviour. In particular, Lloyd (85) has identified various microfaunal groups in two pilot scale SSF using a special sand profile sampler. Bellinger (54) has considered algae in SSF and has identified common species in the supernatant water and those associated with the sand bed. Lodge (86) has carried out an ecological study of the meiofauna of SSF and in particular the Oligochaetes. Bailey (87) undertook a more general study of meiofauna of SSF beds in relation to operational conditions.

Evidence of the existence of micro-organism populations in fabric layers is scanty at present. The Water Research Centre (82) has reported the existence of various algal species in a high porosity fabric but the species were generally similar to those found in the reference filter running parallel to the former. Wheeler _et_ _al_ (84) has identified the presence of Protozoa, Rotifera and Annelida within multiple fabric layers on a pilot SSF unit. The most common protozoa were members of the _Vorticellidae, Tetrahymenina and Oxytrichidae_ species of ciliated protozoa with their densities dispersed throughout fabric layers. From this and other experimental data Wheeler _et_ _al_ concluded that the fabric under study seemed to provide a more favourable environment for ciliated protozoa than sand alone.

1.5.5 Fabric Cleaning

Experience with high porosity fabrics (42,62,82) has showed that the cleaning of fabrics by manual water washing (hosing) presents no difficulties even when substantial algal growth has taken place. However, care is required when removing the fabrics, particularly high porosity fabrics in order not to disturb the silt deposited within the fabric which may fall onto the sand layer supposed to be protected. For more dense fabrics, Bridges (63) has reported difficulties in cleaning even when using a high pressure water jet.

1.5.6 Conclusion

Research work carried out so far has failed to provide adequate information to enable judgement on the suitability of NWF in improvement of operation of SSF to be made because:

(i) The choice of fabrics used in experiments has been largely empirical. No characterization of the potential fabrics in terms of the physical and structural properties which would have helped in preliminary selection was done.

(ii) Previous research work did not consider the complete range of NWF commercially available in the UK market. Apart from Bridges work, only high porosity fabrics (>95%) with low specific surface were used in the trials. This means other more suitable fabrics might have been missed.

(iii) In all cases,the NWF used allowed a large proportion of the influent particulate matter to penetrate into the supporting sand. This accompanied with negligible headloss across the fabrics at the end of the filter runs means that the protection provided was not efficient as ultimately both the fabric and sand had to be cleaned .

(iv) The fabrics used could not stop impurities from sloughing onto the sand bed at the time of lifting the fabric(s) for cleaning.

(v) The results of the previous works did not allow selection of an optimum fabric type and suitable thickness for the water sources studied.

1.6 Objectives Of The Study

The main objectives of this study are presented in two sub-sections as general and specific objectives:

1.6.1 General Objectives

The general objectives of this study were as follows:

1.6.1.1 To make a full characterization (e.g. physical, geometric, hydraulic and filterability) of the NWF commercially available in the UK and to use the information for preliminary selection of fabrics suitable for use with SSF.

1.6.1.2 To extend the filter run times of SSF by optimizing the filterability, thickness and configurations to ensure very low rates of head loss across the fabric(s) .

1.6.1.3 To concentrate the majority of capture of impurities within the NWF such that routine maintenance involves fabrics cleaning only at the end of the filter runs. This would minimize penetration of impurities onto the sand bed.

1.6.1.4 To design optimal NWF configurations preventing sloughing of deposited impurities into the sand underneath if the fabrics have to be lifted during cleaning at the end of the filter runs.

1.6.1.5 To investigate the suitability of NWF for protection of SSF treating water with excess flocs carry-over.

1.6.1.6 To investigate whether or not the use of NWF influences the treatment performance of the protected SSF beds.

1.6.1.7 To investigate some washability aspects of NWF used for protection of SSF beds.

1.6.2 Specific Objectives

In order to meet the general objectives mentioned above, the following studies were undertaken:

1.6.2.1 A survey of commercially available NWF in the UK market was carried out.

1.6.2.2 Theoretical considerations of hydraulic behaviour and filtration mechanisms of NWF were reviewed and a hypothesis of strong dependence of filtration performance on physical and geometric properties (in particular the specific surface area) was formulated.

1.6.2.3 Laboratory experiments were done in order to characterize the clean media hydraulic and filtration performance of NWF. The results of this work were used for initial selection of NWF for field tests.

1.6.2.4 Field experiments were done with a representative range of NWF to test hydraulic and filtration performance in presence of biological processes at a high filtration rate and during substantial algal growth. The main objective of doing these experiments was to narrow down the range of NWF to be tested in the field.

1.6.2.5 Field tests were done in order to select an intermediate specific surface area NWF and to optimize the field hydraulic and filtration performance.

1.6.2.6 Field tests were done to establish the long-term performance of the selected and optimized NWF. These tests also established the treatment contribution of the fabrics.

1.6.2.7 The performance of fabric protected slow sand filters receiving water with excess flocs-carry over from up-flow sludge blanket clarifiers was monitored.

Chapter Two

2. THEORETICAL CONSIDERATIONS OF HYDRAULIC BEHAVIOUR AND FILTRATION MECHANISMS OF NWF

2.1 Fabric Geometric Properties

By combining several fundamental definitions of non-woven fabric physical properties, the relationship of porosity to the specific surface area of clean NWF can be derived assuming the fibres are cylindrical and the diameter is reasonably uniform.

$$\epsilon_o = 1 - (\rho_b / \rho_f) \qquad \textbf{(8)}$$

$$\rho_b = w / z \qquad \textbf{(9)}$$

$$\rho_f = (4 w) / (\pi d_f^2 F) \qquad \textbf{(10)}$$

Where, ρ_b = Fabric bulk density, ρ_f = Fibre specific gravity, w = Fabric weight per unit area, d_f = Fibre diameter z = Fabric thickness (unloaded), ϵ_o = Clean bed porosity and F = Total fibre length per unit area.

Substituting equations **(9)** and **(10)** in **(8)**:

$$\epsilon_o = 1 - (w/z) / ((4 w)/(\pi d_f^2 F)) \qquad \textbf{(11)}$$

Since by definition, $S_o = (\pi d_f F / z)$ **(12)**

Upon rearrangement of **(11)** and subsitution of **(12)**:

$$\epsilon_o = 1 - (d_f S_o/4) \qquad \textbf{(13)}$$

Fig.2.1 shows the relationship given in equation **(13)** for typical fibre diameters and the corresponding values for some fabrics listed in table 1.2 . For comparison, Fig. 2.1 also shows the region of typical values of porosity and specific surface for sand media in SSF . The specific surface for the latter is estimated from the theoretical expression:

$$S_o = 6 (1 - \epsilon_o) / \phi d_s \qquad \textbf{(14)}$$

Where ϕ = Sphericity index and d_s = Filter grain diameter (sieve)

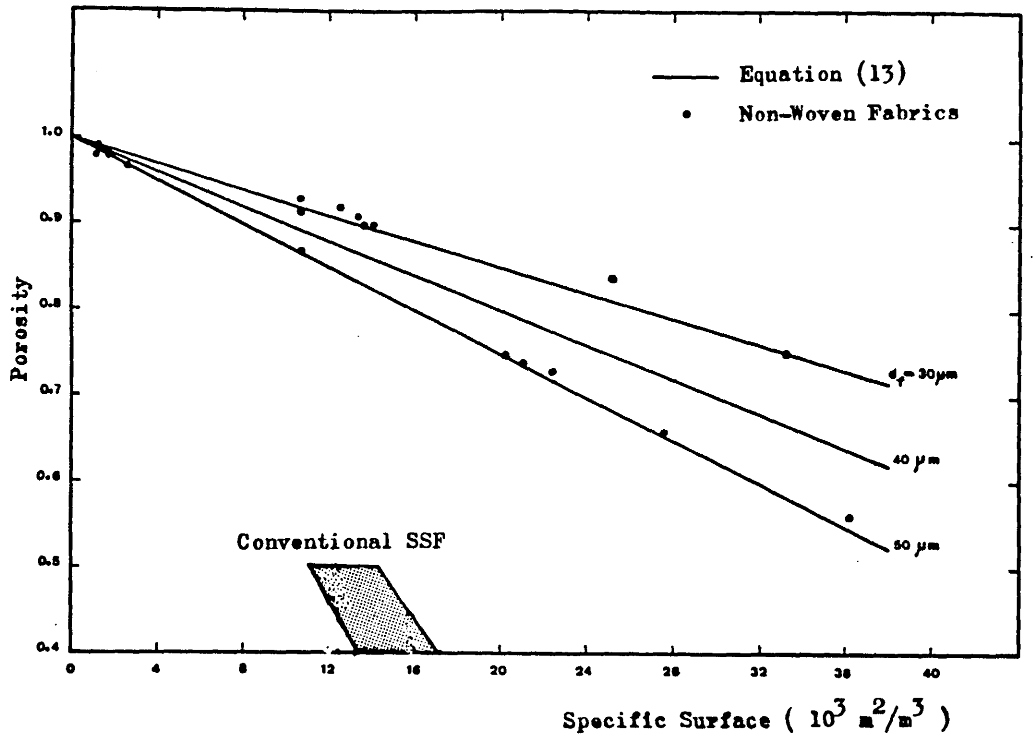


Fig. 2.1 The Porosity - Specific Surface Relationship for Some Non-Woven Fabrics.

2.2 Fabric Hydraulic Properties

It has already been shown that for porous spherical granular media, the permeability can be expressed mathematically in terms of the properties of the media by combining the Carman-Kozeny equation **(2)** and Darcy's equation **(1)** :

$$K = (g k^1 \nu) (\epsilon_o^3 / S_o^2)$$

The Carman-Kozeny filter constant, k^1, is relatively unchanging for many granular media ($k^1 = 4.5 \pm 1$), (88) . For media of high porosity such as NWF ($\epsilon_o > 0.7$), Kozeny's equation does not apply and theoretical values of k^1 increase rapidly with porosity . An important restriction on the use of Carman-Kozeny model is the distribution of pore sizes. Poor results are obtained if the porous medium presents a wide variation in pore sizes as in NWF.

In geotextile applications of NWF, the use of a modified empirical form of Darcy's equation for determination of fabrics coefficient of permeability is common (89 - 91) :

$$i = k_f v^b \qquad \textbf{(15)}$$

Where, i = Hydraulic gradient , v = Approach velocity, k_f = The turbulent coefficient of permeability and b = An empirical constant ranging from 1.0 to 2.0 .

For purely laminar flows , b = 1.0 while for purely turbulent flows b = 2.0 . Transition flows are represented by intermediate values of b . However, the fact that the method used to determine k_f is rather complex and both k_f and b are not parameters commonly used to characterise other porous media makes this technique of little practical relevance.

Another common method amongst geotextile NWF users is to express the fabric permeability in terms of the volume of water passing / unit area / unit time / unit water head (90). Its popularity is based on test simplicity and ease of comparison between different fabrics. However, one disadvantage of this method is that volume of flow cannot be compared directly with permeability of other porous filter media.

While it is clear that Darcy's equation for porous media is valid under laminar flow conditions, one must be careful in applying flow analysis used for granular media to NWF (92). Literature (89,93) has shown that the flow regime through porous granular media remains laminar for Reynold's Number Re less than 10 . This observation is strictly valid for porous media with a porosity of less than 50 % like sand. However, apart from spunbonded and some thermic bonded NWF, the porosity of most NWF is greater than or equal to 75 % (table 1.2) .

If the Hagen-Poiseuille equation for laminar flow in tubes is used to evaluate the friction factor and the corresponding Reynold's Number (Re) of NWF, one can wrongly conclude that the critical Re at which Darcy's law cannot be applied for NWF is lower than for granular media. However, since the porosity of most NWF is much higher than granular media such an observation would obviously not be true. Rollin *et al* analytical model (92) has been successfully used to overcome the problem of definition of laminar flow regimes in fibrous media. The model assumes a flow around a single cylinder and a bundle of cylinders as shown on Figs. 2.2 (a) and (b), respectively. As the fluid flows around a fibre, a drag force (F_d) in the direction of flow is exerted by the fluid on the fibre/cylinder. Therefore a single cylinder/fibre drag coefficient C_d can be defined by the equation:

$$F_d = C_d \; S_c \; K_e \qquad \textbf{(16)}$$

On re-arrangement, the drag coefficient can be expressed as :

$$C_d = (F_d \; / \; S_c \; K_e) \qquad \textbf{(17)}$$

Where, F_d = Drag force, S_c = Characteristic or projected area and K_e = Kinetic energy term.

Dimensionless analysis can show that C_d is a function of Re which is in turn defined as :

$$Re = \rho \; v_b \; d_f / \; \mu \qquad \textbf{(18)}$$

Where, v_b = Velocity in the bulk of the fluid.

ρ = Fluid density.

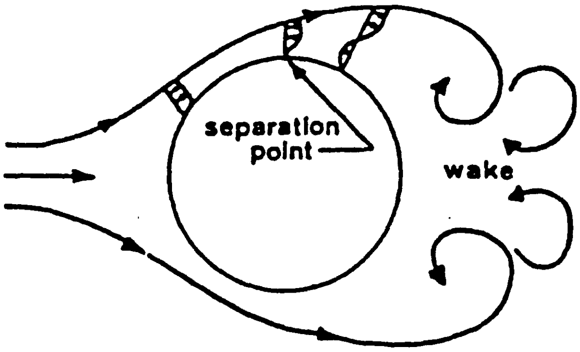
d_f= Fibre/Cylinder diameter.

μ = Dynamic viscosity.

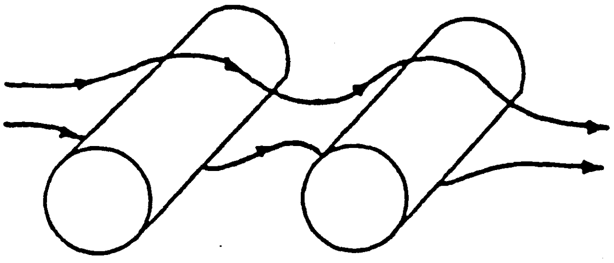
Experimental results of the correlation of the dimensionless single cylinder drag coefficient (C_d) to Re from various researchers are shown on Fig. 2.3 (92) . For the case of a bundle of in-line tubes of heat exchangers indicated, the prescence of adjacent cylinders (tubes) affects the flow pattern around each of them such that as the distance between the cylinders is decreased, the higher is the flow rate at which separation point appears thus shifting the transitional flow regime to higher Re . In fact, as can be seen in Fig. 2.3 , the critical Re at which the laminar flow regime does not exist any more is greater for flow through a bundle of tubes than for the single cylinders. Upon extending the theory of pressure drop through a bundle of cylinders (94) to NWF and if it can be assumed that for the NWF the fibres are arranged as a series of rows with a reasonably square pitch, the following expressions can be derived:

$$Re = \rho v_e d_f / \mu \qquad (19)$$

$$C_d = g i / N v_e^2 \qquad (20)$$



(a) Flow pattern around a cylinder at transitional flow regime.



(b) Flow pattern around two cylinders/fibres.

Fig. 2.2 Schematic flow pattern around a cylinder and around two cylinders/fibres, after Rollin _et al_, (92).

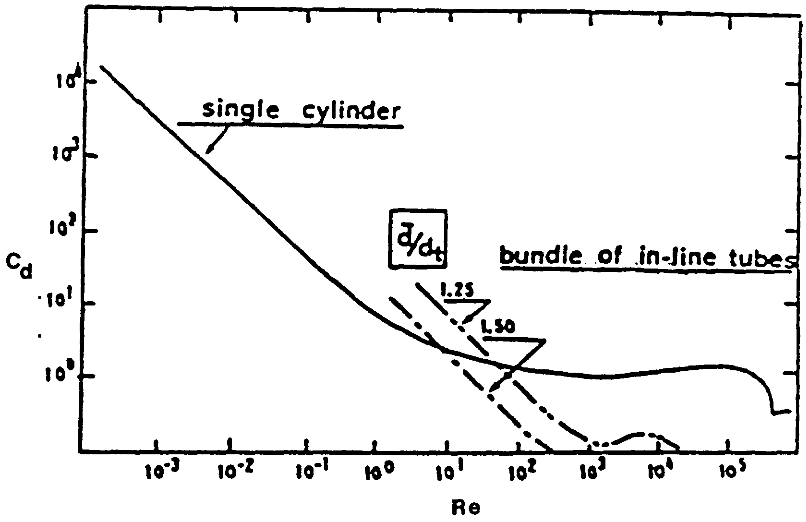


Fig. 2.3 Drag coefficient around a cylinder and a bundle of tubes, after Rolin _et al_, (92).

Where, $v_e = v/\epsilon_o$ = Effective velocity in the fabric,
N = The number of rows of fibres, i = Hydraulic gradient.

N can be found from the equation :

$$N = z / (\bar{d} + d_f) \qquad \textbf{(21)}$$

$\bar{d}$ = The mean distance between the fibres,
z = Fabric thickness and d_f = Fibre diameter .

The mean distance between the fibres can be measured using an image analyzer as described elsewhere (95) or can be estimated using probabilistic equations (96) based on fabrics physical and geometric properties. Fig. 2.4 gives the correlation of C_d to Re for some NWF tested (92), it also indicates the same for bundles of in-line tubes. An expression for the hydraulic conductivity derived for the NWF tested in this particular case (92) was found to be :

$$K = d_f \, (d_f + \bar{d}) \, \epsilon_o \, \rho \, g / A \qquad \textbf{(22)}$$

$$C_d = A / Re \qquad \textbf{(23)}$$

Where, A = An empirical correlation coefficient found to range from 6 to 10 depending on the ratio $\bar{d} / d_f$.

This study confirmed the existence of the relationship between C_d and Re thus supporting the proposed model of laminar flow through a bundle of fibres/cylinders . The model allows a theoretical prediction of the pressure drop across the fabrics to be made with the help of physical and geometric properties. However, to date this model has not been widely adopted and used by other researchers to sufficiently test its validity, sensitivity and limitations. The high costs of acquiring equipments required for experiments (e.g. Image analyzer) and the substantial amount of time required in preparation of the NWF samples before analysis on the Image analyzer might be responsible for reluctance of other workers to test the model.

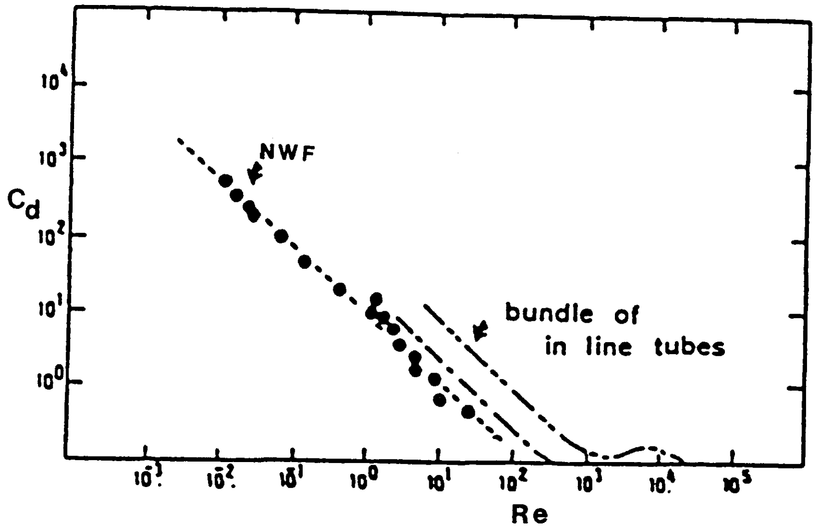


Fig. 2.4 The Correlation of C_d to Re for Some NWF, after Rollin et al, (92).

Three models commonly used for theoretical prediction of permeability and pressure drop across fibrous media can be found in the literature, Happel (97), Kuwabara (98) and Spielman & Goren (99). The first two are based on equations of creeping flow and are referred to as cell models. Happel's model for arrays of cylinders associates a co-axial cylindical cell with each fibre element. The solid cylinder is taken to move within the cell with a superficial velocity, v. No slip boundary conditions are assumed at the solid-cylinder surface with the outer cell boundary a free surface. Kuwabara's model is very similar to Happel's except the outer boundary condition of free surface is replaced by vanishing vorticity. Using cylindrical coordinates (r, θ) with the origin at the centre of a representative cylindrical collector and expanding in power series for $(r - a_F)$ from the cylinder surface (9), the stream function becomes :

$$\Psi = [\, 2\, A_F(\gamma)\; v\; (r - a_F)^2 \sin\theta \,/\, a_F] \qquad \textbf{(24)}$$

Where, a_F = Fibre radius , v = Approach velocity,

r = Radial coordinate, θ = Angular coordinate and

$A_F(\gamma)$= A dimensionless flow model parameter(function of γ)

With γ = Volume fraction of fibres in the array, Happel's model gives :

$$A_F(\gamma) = 1 / [-\ln\gamma - 1 + \gamma^2 / (1 + \gamma^2)] \qquad \textbf{(25)}$$

In turn, Kuwabara's model gives :

$$A_F(\gamma) = 1 / (-\ln\gamma - 3/2 + 2\gamma - \gamma^2 / 2) \qquad \textbf{(26)}$$

Spielman and Goren (99) applied Brinkman's model for flow through a swarm of spheres (100) to fibrous media. Its essence is that the fluid in proximity to a representative element within the array of cylinders experiences a body damping force proportional to the velocity in addition to the pressure and viscous forces, the damping force accounts for the influence of neighbouring elements on the flow. With the stream function as given by equation **(24)**, and $A_F(\gamma)$ given by parametric equations :

$$A_F(\gamma) = \beta K_1(\beta) / 2 K_0(\beta) \qquad \textbf{(27)}$$

$$\gamma = 1 / [2 + 4K_1(\beta) / K_0(\beta)] \qquad \textbf{(28)}$$

K_0 and K_1 are Bessel functions of Zero and first order and

β = A dummy parameter for determination of pairs of $A_F(\gamma)$ and γ at fixed values of β .

Brinkman's model breaks down when the packing density becomes too large and as a result it over-predicts pressure drop for densely packed beds. Moreover, the parametric representation in terms of Bessel functions makes this model less convenient for application than Happel and Kuwabara models.

Theoretical values for permeability of fibrous media may therefore be determined by employing either of the two cell models discussed. Happel and Kuwabara's models produce explicit expressions for the permeability in terms of fibre size and media porosity . These models have been well tested by many other workers (101 - 103) . However, in most cases, Happel's model seems to fit experimental results better than Kuwabara's . For Happel's model :

$$k_h = d_f^2[-\ln \gamma - (1 - \gamma)^2/(1 + \gamma^2)] / 32 \qquad \textbf{(29)}$$

While for Kuwabara's model :

$$k_k = d_f^2(-\ln \gamma + 2\gamma - \gamma^2/2 - 3/2) / 32 \qquad \textbf{(30)}$$

Where, $k_h = k_k$ = The permeability factor = ($K \nu / g$)

Regarding the complete blockage of NWF expected to occur at the end of the filter run time, it is likely that the head loss profile would closely follow the so called Boucher's law which is reported to have an exponential increase pattern given by (104,105) :

$$H_s = k_s \exp (k_q t) \qquad \textbf{(31)}$$

Where , H_s = Headloss due to surface deposition ,
k_s = Initial head loss at the surface and
k_q = Head loss coefficient.

k_q is usually determined empirically. Since equation **(31)** has been found to describe the phenomenon of surface deposition in deep bed filters, it is assumed that the same can be used to describe the head loss across a completely blocked NWF at the end of the filter run time.

2.3 Mode of action of NWF

Depending on the manufacturing technique, physical and chemical composition of fibres and the characteristics of the raw water to be filtered; the fundamental transport mechanisms discussed in the previous chapter can be operative within NWF protecting SSF beds . A reliance of particle attachment upon electrostatic conditions, Van der Waal's forces, adhesion and biochemical processes should be expected. In NWF; surface-, depth-, adsorptive- and biological-filtration phenomena can be identified, three of these are schematically shown on Fig. 2.5 . It should be noted that in reality these phenomena do not occur separately but often do so in unison within a NWF.

2.3.1 Surface Filtration - This involves screening or straining of particles larger than pore sizes. Occasionally small particles which arrive at the fabric surface simultaneously might be removed by bridging the pores. An additional surface filtration related phenomenon is the deposition of particles on the NWF surface as a result of sedimentation taking place due to the long detention times of supernatant water in SSF beds.

2.3.2 Depth Filtration - This occurs when particles penetrate into the filter medium and become trapped in the tortuous paths due to its winding nature or fibre roughness. Obviously a particle with a diameter smaller than the top pore opening will be trapped in the fabric if its pore diameter narrows with depth. Increasing the depth of the fabric increases the predominance of this phenomenon.

2.3.3 **Adsorptive Filtration** - This involves removal of particles when they come in contact with and adhere to the fibre surfaces. This takes place throughout the fabric volume and particles smaller than pore sizes are retained due to diffusional movements related to Brownian motions of submicron particles. Favourable fibre-particle surface charge characteristics encourage this phenomenon. An efficient adsorptive filter will therefore have to present a large surface area to the particles so as to increase the particle capture probability. NWF exhibit high specific surfaces (table 1.2) , thus indicating their high adsorption potential. Depth and adsorptive filtration phenomena are sometimes jointly referred to as deep bed filtration mechanisms in literature (76) .

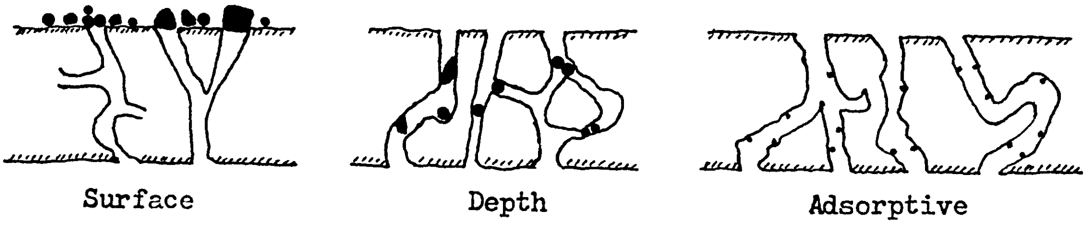


Fig. 2.5 Some dominant filtration phenomena in NWF.

2.3.4 Biological Filtration - This is expected to take place on the surface and in the depth of the fabric. The formation of the surface biological skin (schmutzdecke) in the top layer(s) of the NWF and around all fibres during ripening stage is expected to intensify straining and removal of unwanted micro-organisms. Further biochemical activities will be expected to take place throughout the fabric depth involving oxidative processes and activities of motile species of living organisms. Biological activities are also expected to increase the strength and adhesion probability of submicron particles.

Similar to observations with membrane stack filters (106), another filtration mechanism found in NWF which is less pronounced in most granular media is the permeation through a substantially higher number of interstices in bundles of fibres especially when multi-filament scrims are used to manufacture needle-felted NWF. For a NWF placed on top of SSF beds, during the greater part of the filter run time a combination of the mechanisms discussed is operative. However, a few days before the end of a filter run, straining and biological filtration mechanisms are expected to predominate.

2.4 NWF Morphological Models

A number of attempts to model NWF structure as filter media have been undertaken, here the work of Abdel-Ghani et al (107), Lombard et al (108) and Masounave et al (95) is briefly reviewed. Abdel-Ghani et al (107) modelled a NWF with negligible fibre entanglement (Non-needlefelted) by assuming randomly distributed fibres from which a statistical distribution of pore sizes in shape of polygons could be obtained. The fibre size distribution was also modelled in this case. However, the filtration criterion used was only relevant to screening which would not present an acceptable design basis for NWF protecting SSF beds.

Lombard et al (108) modelled thin heat-bonded non-woven synthetic fabrics using the analytical geometric probability approach for deriving pore size distribution functions. For this purpose, the Poisson polyhydrons theory (109) was used to derive an expression for pore size distribution of circles inscribed in the simulated polygons. The fibres were assumed to be straight and of infinite length . A further assumption of pores being straight capillaries normal to the NWF plane with a length of two fibre diameters was made. In this case, the final pore size distribution was expressed as a function of the physical and geometric properties of the fabrics. The pore opening sizes of the modelled NWF were measured by dry sieving of glass beads and hydrodynamic filtration tests.

A good qualitative agreement was obtained between results measured by hydrodynamic filtration and opening sizes calculated by the model. However, although the pore size distributions are of interest in design of NWF multi-layers for protection of SSF, the final results of this work are more likely to be of interest for geo-technical filtration applications.

Masounave et al (95), attempted to model typical needlefelt fabrics representing randomly distributed fibres with the help of an image analyzer and application of a semi-Markovian distribution (110) to describe morphological properties . This work succeeded in describing the hydraulic properties and filtration behaviour of NWF used for soil retention in soil drainage applications.

Although the use of statistically based modelling to characterize NWF characteristics seems to be well established, the paucity of experimental results from other workers in this field has made it difficult to test the extent of validity of the models derived to date. Currently, there isn't any reliable apparatus for characterizing morphological properties of NWF accurately which would confirm these research findings.

2.5 Fabric Filterability

The filterability of a filter medium refers to its ability to remove particles from a flowing suspension. For granular media, and particularly under clean bed conditions at the commencement of filtration, theoretical models for the filtration process are well established. The fundamental theoretical hypothesis is already given in equation **(4)** . For a filter of uniform fibres a simple theoretical approach considers the collection efficiency of a single fibre. Thus, the overall filter performance is related to the single fibre collection performance by equating the difference in particle concentration entering and leaving to the net collection by all fibres in a differential depth dL of the filter :

$$-v\ dC\ /\ dL = I\ (\ 4\gamma / \pi d_f^2) \qquad \textbf{(32)}$$

Where, C = Suspension number concentration,

v = Approach velocity, d_f = Fibre diameter,

I = The average rate of collection of entrained particles per unit length of fibre.

γ = Volume fraction of fibres.

If isolated particle-fibre encounters are predominantly responsible for particle removal, I is directly proportional to C and it becomes convenient to introduce the dimensionless single fibre efficiency η_f defined as :

$$\eta_f = I \ (d_f \ v \ C \ )^{-1} \qquad \textbf{(33)}$$

Substitution of equation **(33)** into equation **(32)** to eliminate I gives :

$$-dC \ / \ dL = (\ 4 \gamma \eta_f \ / \ \pi \ d_f) \ C \qquad \textbf{(34)}$$

The single fibre collector efficiency can be considered as the product of the overall single fibre collector transport efficiency, η , and the particle-fibre attachment efficiency, α, and hence :

$$- \ dC \ / \ dL = (\ 4 \gamma \eta \alpha \ / \ \pi \ d_f \ ) \ C \qquad \textbf{(35)}$$

From equations **(4)** and **(35)** , the filter coefficient can be expressed as :

$$\lambda = 4 \gamma \eta \alpha \ / \ \pi \ d_f \qquad \textbf{(36)}$$

By expressing the filter coefficient in terms of the specific surface area of fibres as in equation **(13)** , equation **(36)** becomes:

$$\lambda = S \ (\ \eta \alpha \ / \ \pi \ ) \qquad \textbf{(37)}$$

Where, S = Specific surface area of the filter media per unit bed volume.

While from the above equation, it would appear that the fabric filtration coefficient is simply dependent on the specific surface of the fibres, experimental evidence and deeper theoretical analysis of particle trajectories have shown that it is also dependent on the flow velocity, fibre diameter, particle size and density. This may be explained by considering two dominant transport mechanisms.

For suspension particles of diameter bigger than 1 μm passing vertically downwards through a fabric layer, the classical transport mechanisms of most significance are interception and sedimentation. Based on single cylinder models (9) :

For interception : $\eta_I = 2 A_F(d_p/d_f)^2$ **(38)**

Provided d_p / d_f is less than 0.1 .

d_p is the particle diameter .

For co-directional sedimentation:

$$\eta_s = (1 + d_p/d_f) v_s/v \quad \textbf{(39)}$$

Where , v_s is the Stokes settling velocity of the particle.

On assuming additivity, the combined transport efficiency can be expressed as :

$$\eta = \eta_I + \eta_s \quad \textbf{(40)}$$

In qualitative terms , the transport efficiency is expected to increase with particle size (also density) and decrease with flow velocity and fibre size.

The attachment efficiency, α , is considered to be determined by the net effect of Van der Waal's attraction force between particles and fibres, and resistive forces. The resistive forces arise from the electrical double layer interactions and viscous fluid forces when separation between a particle and a fibre is of the order of one particle diameter .

Chapter Three

3. LABORATORY STRUCTURAL, HYDRAULIC AND FILTRATION CHARACTERIZATION OF FILTER MEDIA .

Scanning Electron Microscope (SEM) observations were done in order to check the physical appearance and disposition of the fibres of virgin NWF, to establish the surface and cross section morphology of the fabrics and to compare the structure of both used and unused NWF. The objective of carrying out permeability experiments were to demonstrate the validity of Darcy's law in a representative range of NWF and to show the applicability of cell models in hydraulic characterization of NWF. Another equally important objective was to make a preliminary assessment of the suitability of NWF for protection of SSF sand beds on the basis of their virgin and used state hydraulic conductivities in comparison to SSF sand. Filterability experiments were done in order to qualitatively establish the clean bed filtration performance of a representative range of NWF and to show the validity of the proposed hypothesis of substantial dependence of NWF filterability on the physical properties and specifically the specific surface area. The results of these experiments were used as a guideline for initial selection of NWF for field tests.

3.1 Scanning Electron Microscopic (SEM) Structural Characterization of NWF.

3.1.1 Materials and Experimental Procedure

Glass slides were cleaned with analar grade methanol (BDH, UK) and left to dry for a while prior to mounting the virgin (new) or used NWF samples using Devcon araldite (Wellingborough,UK), a mixture of two separate tubes of Epoxy and Polyamine resins. The list indicating the type and condition of fabric samples analyzed is shown in table 3.1 . A number of used fabric samples analyzed were taken at the end of a field test programme which lasted for about three months. Each of the used fabrics lab. No. 44 and 55 had been washed at least 17 times during a field test programme. The NWF lab. No. 32 had been washed only 5 times due to its longer filter run times. It was expected that SEM analysis would have clearly shown the extent of blinding of the NWF which was demonstrated by successively decreasing filter run times during the field test programme. For each fabric sample, three representative surface and three cross-section samples were analyzed.

Table 3.1 Fabrics subject to SEM analysis.

Fabric Lab. Number	Condition of samples analyzed
25	Virgin only
26	Virgin only
27	Virgin and used
28	Virgin only
32	Virgin and used
44	Virgin and used
55	Virgin and used

The slide-mounted NWF specimens were then mounted on aluminium pin type stubs and gold coated using an Edwards E306A sputter coater. A silver suspension was then applied to the junction of the specimens and the stubs. A JEOL JXA-733 (Jeol Ltd., Tokyo, Japan) electron probe X-ray microanalyzer was then used to examine the specimens in secondary electron mode. Fig. 3.1 shows a general view of the JXA-733 scanning electron microscope (SEM) system used while Fig. 3.2 gives a close-up of the console in which the specimens were mounted.

3.1.2 **Results**

Observation of the surface properties of virgin fabrics revealed some structural and fibre physical properties which could not be seen by the naked eye. For example, plate.1 clearly shows the differences in fibre diameters in the virgin fabric lab. No. 26 which are also presented in table. 1.2. While plates.2 and 3 show the surface characteristics of virgin fabric lab. No. 27 and 28, respectively, observation of fabrics lab. Nos. 25 and 32 showed the characteristic irregularity and roughness of fibres which are likely to be dependent upon both fibre production and bonding techniques. The influence of finishing processes like calendering on virgin NWF

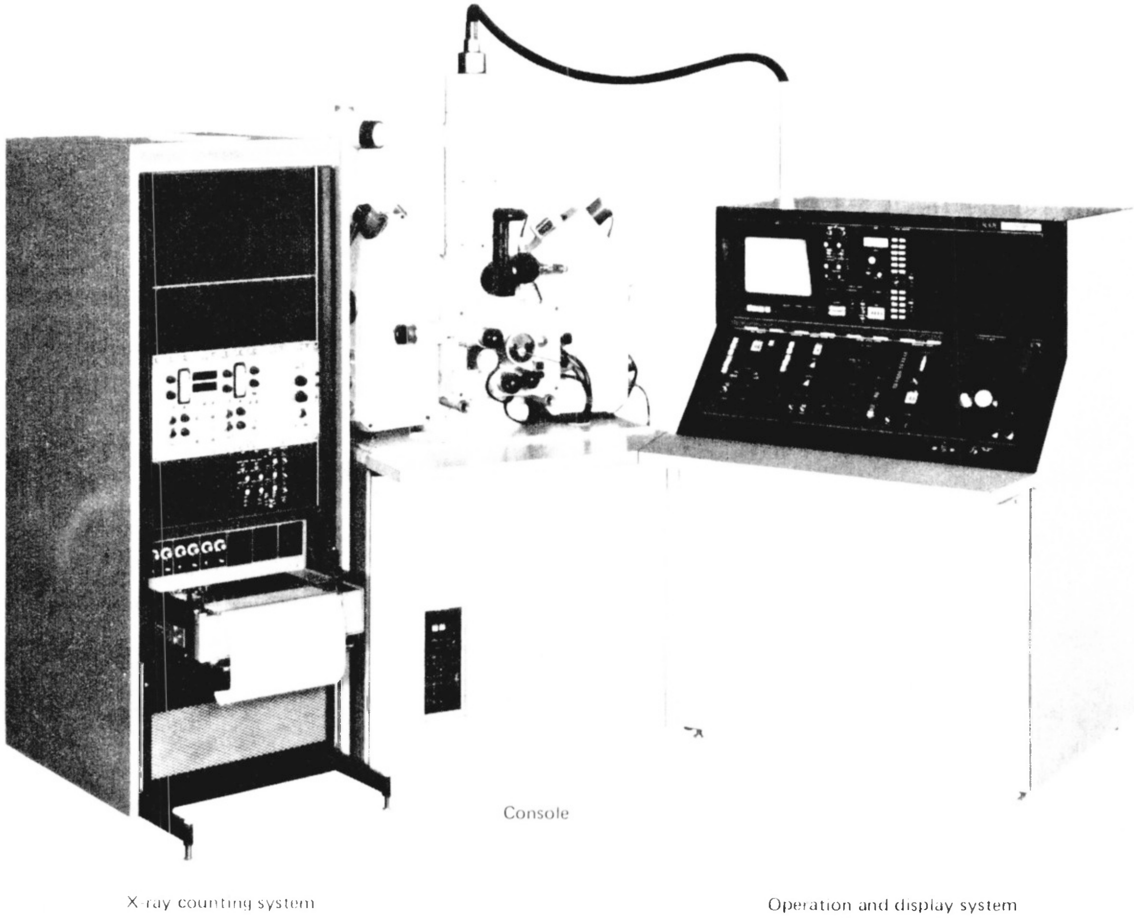


Fig. 3.1 The general view of the JXA - 733 .

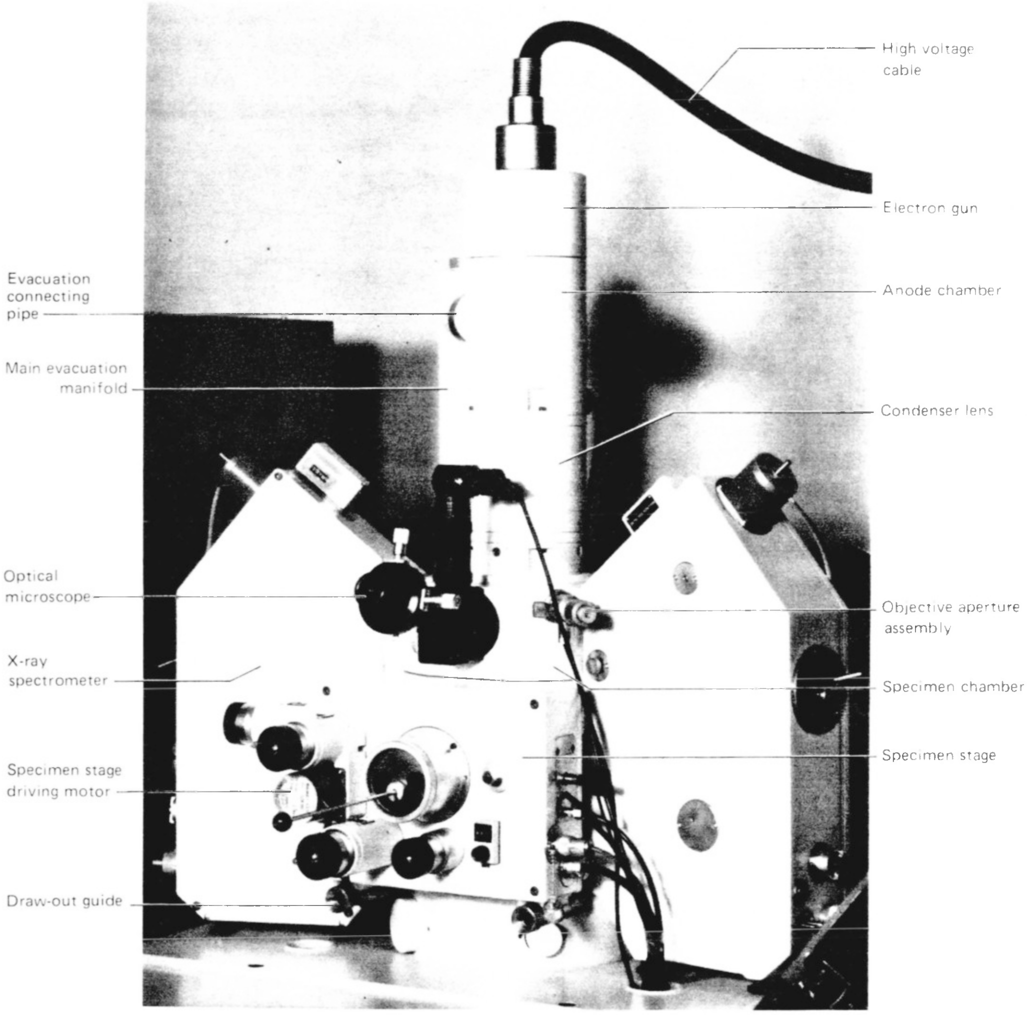


Fig. 3.2 The console close-up (Column & X-ray spectrometer).

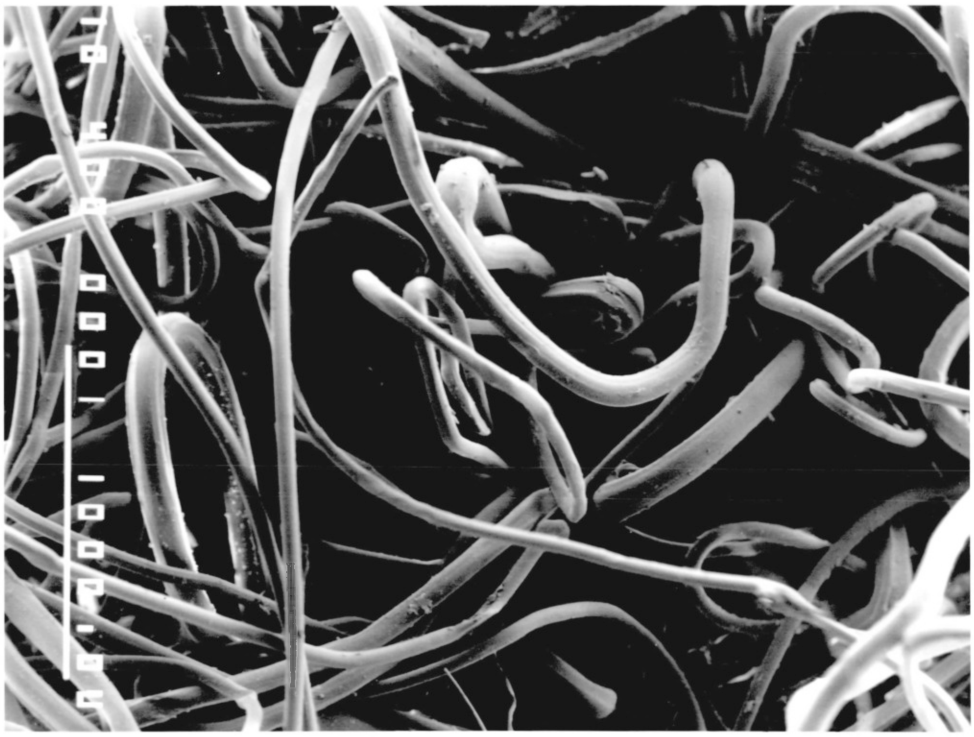


Plate.1 Surface Appearance of Virgin Lab. No.26·

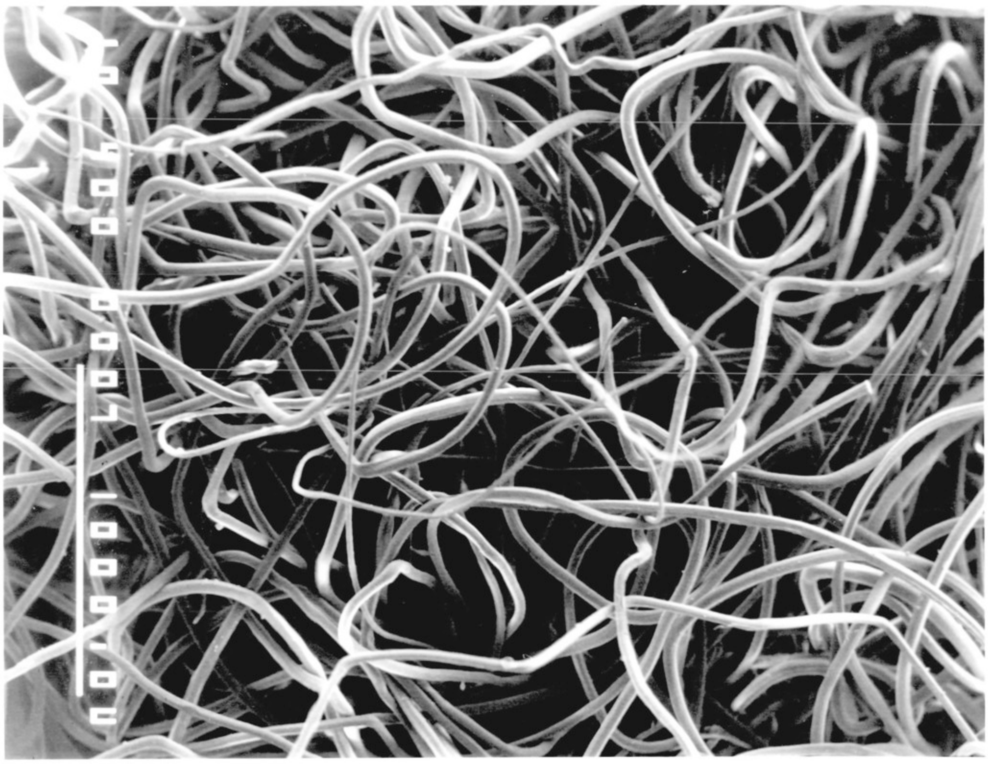


Plate.2 Surface Appearance of Virgin Lab. No.27·

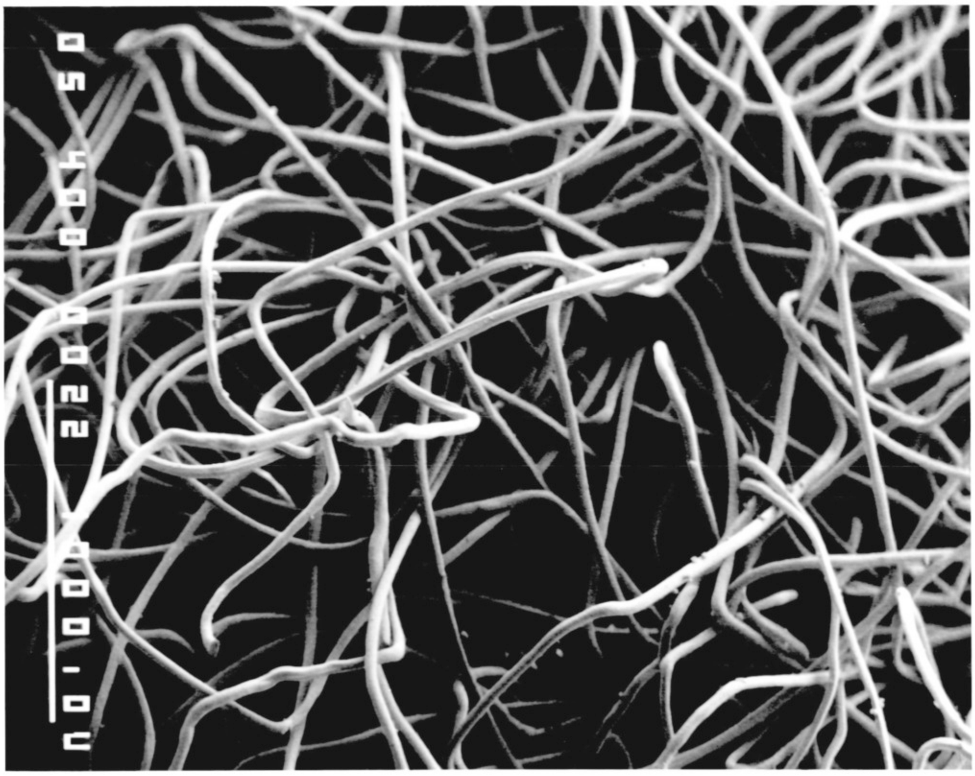


Plate.3 Surface Appearance of Virgin Lab. No. 28.

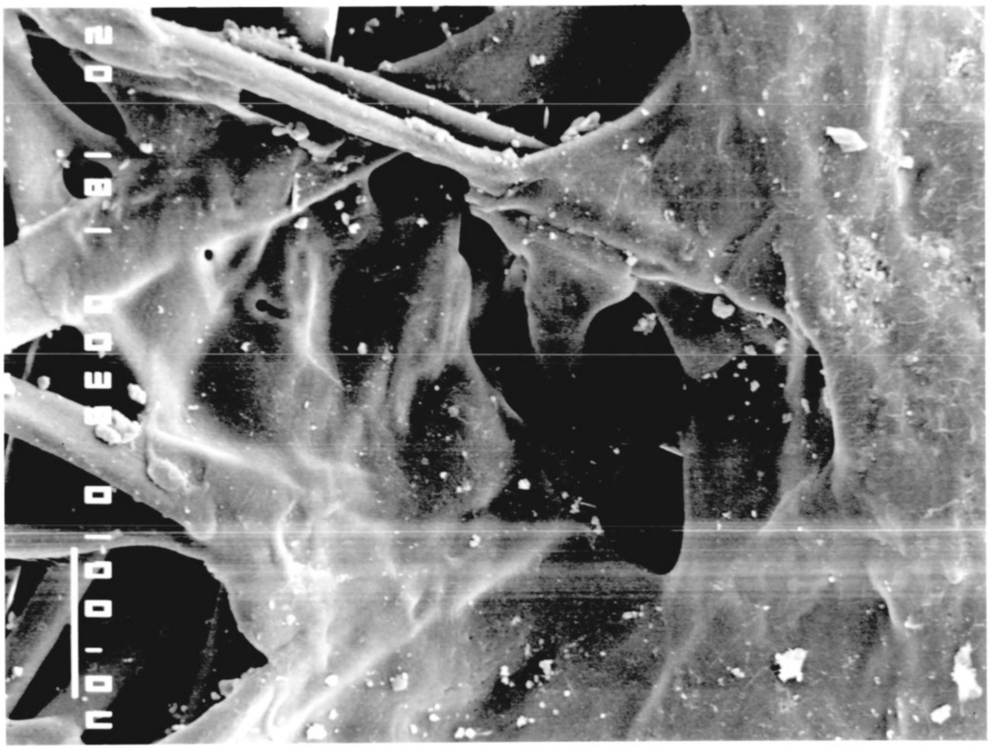


Plate.4 Pore Blinding Due to Calendering, Lab. No. 44.

morphology with respect to blinding of some pores can be seen in plate.4 . A close look of the surface of the thermic bonded fabric lab. No. 55 at high magnification showed the existence of holes on fibres as can be seen in plate.5 . Such fibre roughness can improve particle capture efficiency in a manner previously suggested by Gimbel et al (106).

Observation of the cross section samples of NWF lab. Nos. 44 and 55 in plates. 6 and 7 , respectively, showed the influence of fabric manufacturing processes on morphology. The most important observation with respect to the cross section of NWF was establishment of some basic differences in structural properties of fabric lab. No. 27 and 28. Plate.8 shows that fabric lab. No. 28 was needlefelted on multi-filament yarn scrims rather than monofilament thread used in fabric lab. No.27 . Plate.9 shows a close-up of the multi-filament scrim yarn in lab. No.28 at a higher magnification . This observation might have accounted for the difference in filtration performance of fabrics lab. No. 27 and 28 observed later. Analysis of used fabrics showed different extents of blinding as exemplified by plates.10 and 11. In general, this analysis helped to give a better assessment of NWF internal morphological properties especially in terms of fibre physical properties and the fabric structure.

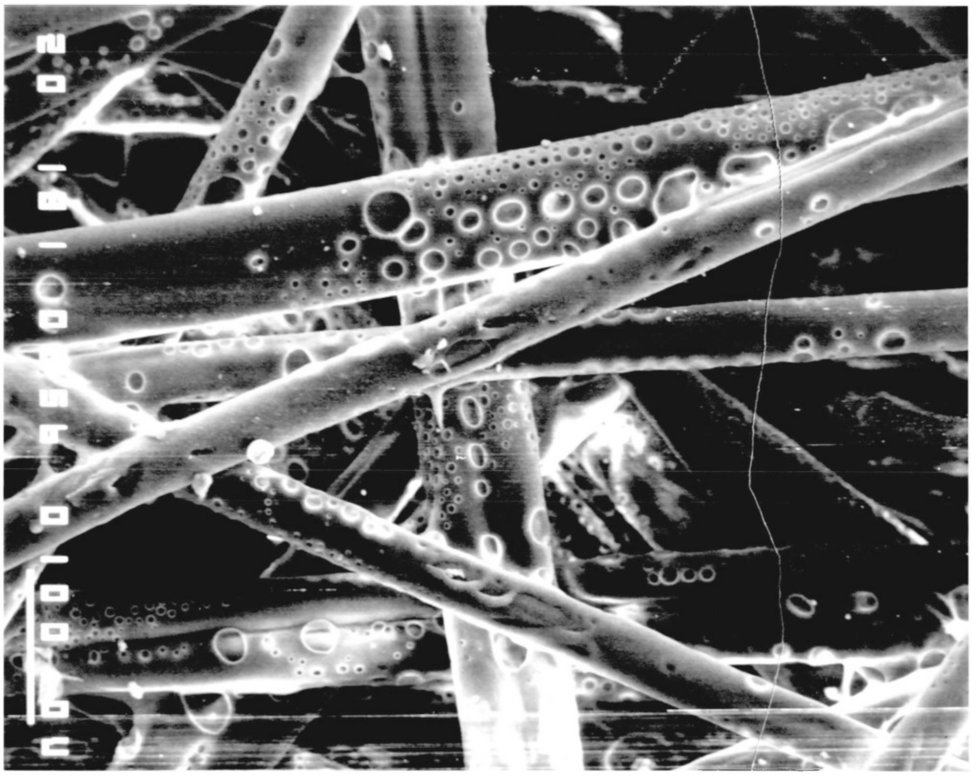


Plate.5 A Close-Up of Virgin Lab. No. 55.

Plate.6 Cross Section of Virgin Lab. No.44.

Plate.7 Cross Section of Virgin Lab. No. 55.

Plate.8 Cross Section of Virgin Lab. No. 28.

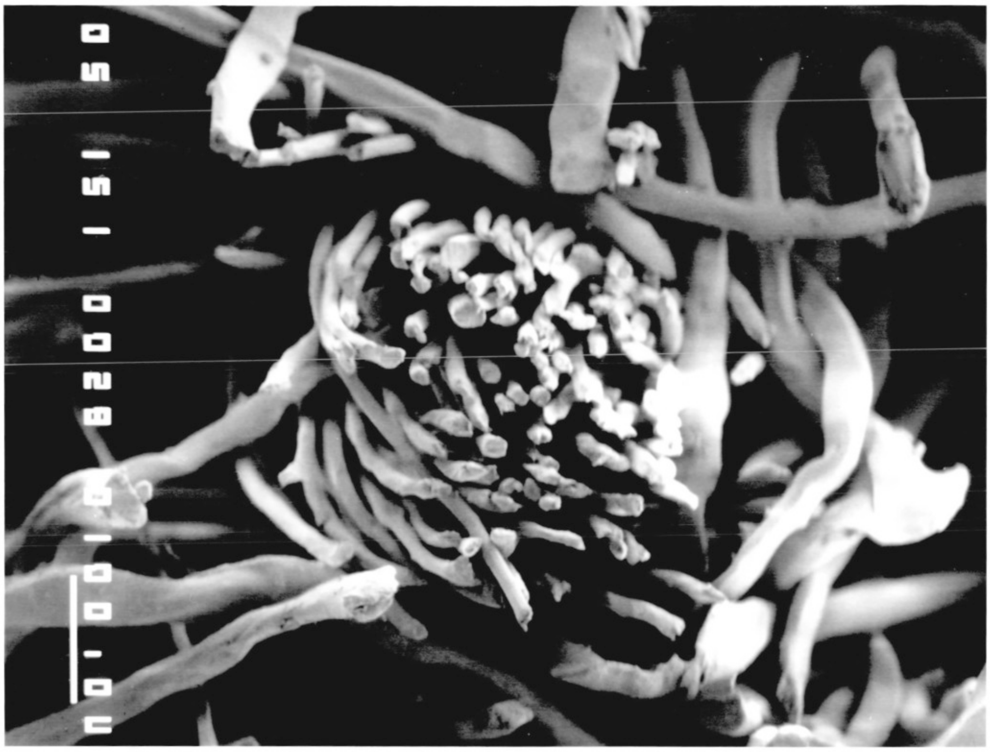


Plate.9 Close-Up of Virgin Lab. No. 28 Cross Section.

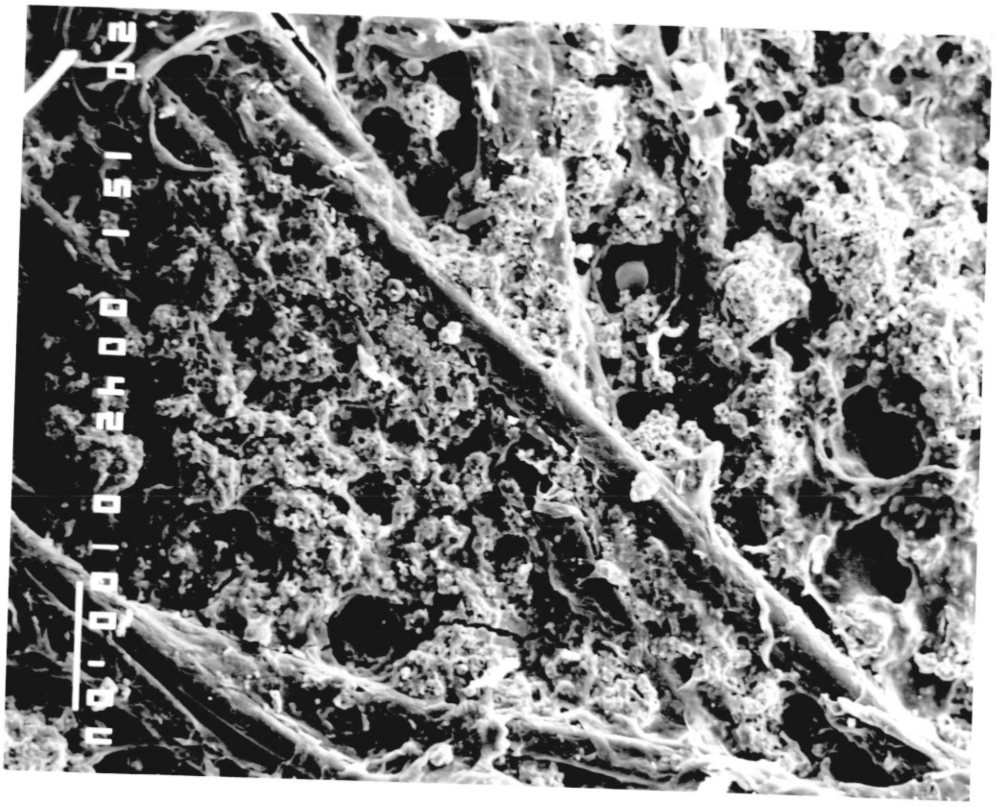


Plate.10 Blinding of Used Lab. No. 55.

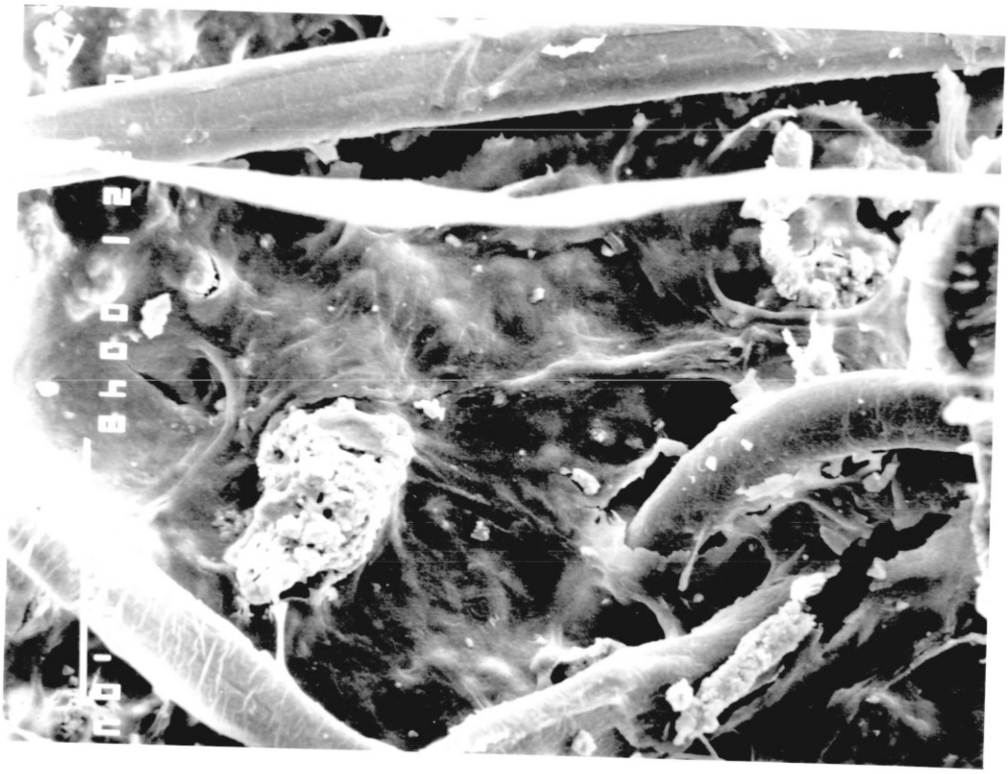


Plate.11 Blinding of Used Lab.No. 44.

3.2 Filter Media

Out of the NWF listed in table 1.2 only 14, nearly representing the complete range of geometric properties of those commercially available in the UK market, were initially selected for laboratory permeability experiments (table. 3.3) . However, of these, only 8 fabrics were considered during the subsequent laboratory filterability experiments as listed in table 3.4 . In order to be able to compare the performance of SSF sand with NWF, a sample of sand used for filtration during field tests at Ashford Common pilot plant was also subject to both hydraulic and filtration characterization in the laboratory. The mean grading of SSF sand used is shown in Fig.3.3 . The sand sieve analysis was carried out according to BS 1377:1975 (111) . From the observed results, the effective diameter (d_{10}) was 0.30 mm while the uniformity coefficient (d_{60}/d_{10}) was 2.1 . The results are in conformity with literature with regard to acceptable ranges of effective diameter and uniformity coefficients (5,6) .

3.2.1 Fabrics Cutting

NWF samples used for both hydraulic and filtration experiments were precision-cut to a circular shape with a diameter of 141.5 ± 0.52 mm (95% confidence) meant to fit tightly in the perspex column measured to have a mean diameter of 141 ± 0.12 mm (95% confidence). Each fabric

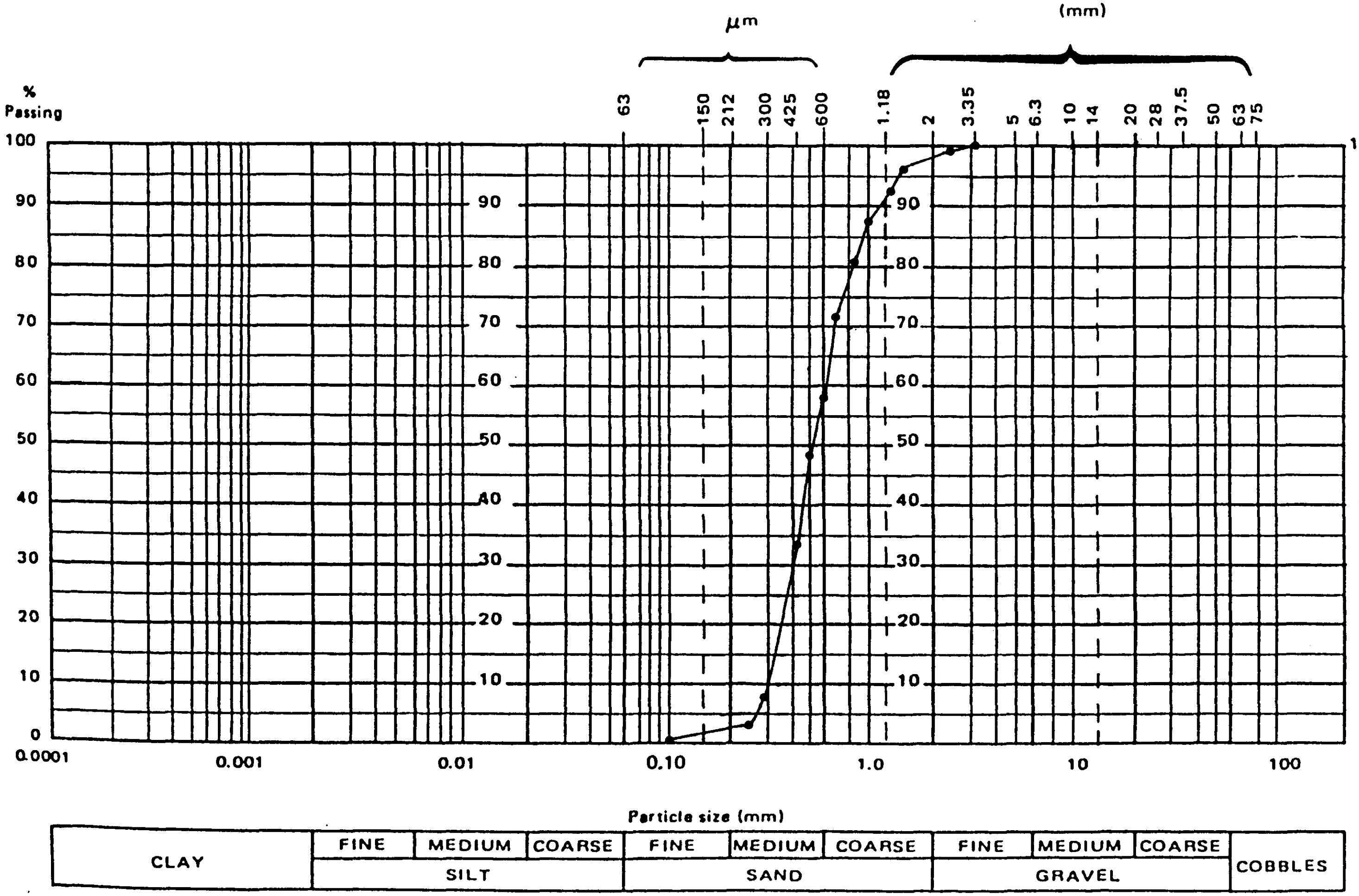


Fig. 3.3 The SSF Sand Mean Grading Curve.

sample was individually cut with a sharp steel die connected to a screw-type Fly press as indicated on plate.12 . The dye was designed and manufactured at Imperial College especially for this purpose.

3.2.2 Filter Media Cleaning

In order to ensure that the NWF samples were free from any unwanted impurities they were kept in a 2% completely rinsable alkali detergent solution (Decon 90, BDH, UK) for one hour. Then the fabric samples were rinsed three times prior to soaking in de-ionized water for at least 24 hours before use. While the time of exposure of fabrics to the detergent solution was kept to a minimum, SSF sand was soaked for six hours in 2% Decon 90 solution prior to rinsing in a similar manner. It must be noted that the chances of sand grains from natural quarries having substantial amounts of unwanted impurities are much higher than for a virgin NWF .

3.3 Permeability / Filtration Column

The main experimental rig consisted of an 141 mm internal diameter perspex column (manufactured at Imperial College) comprising of three main parts of which either all or only two could be assembled together by flanged connections (see Fig. 3.4). The rig was made in such a way that it could either be used for hydraulic conductivity or filterability experiments. In each case, the filter medium under

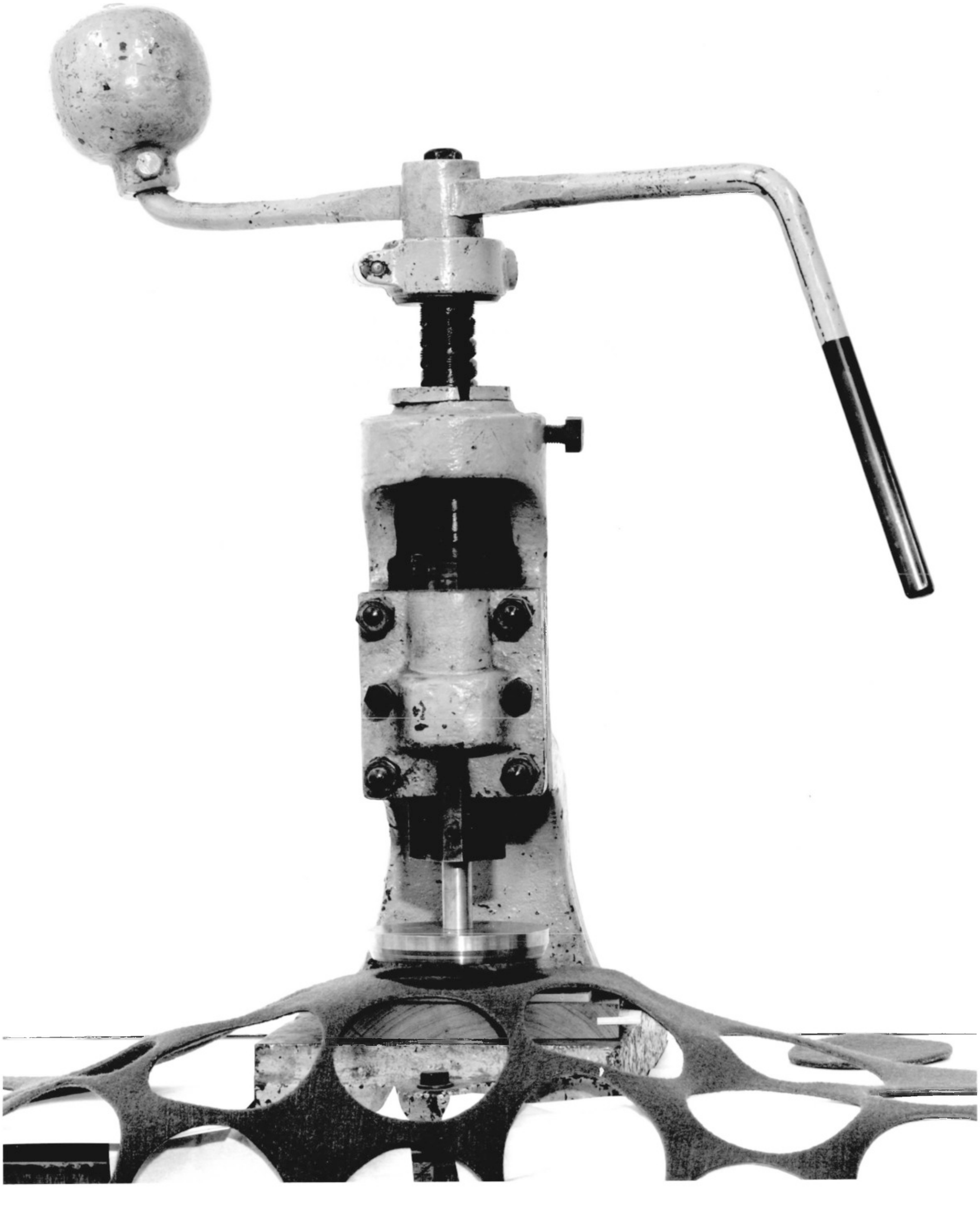


Plate.12 Cutting of Non-Woven Fabrics with a die.

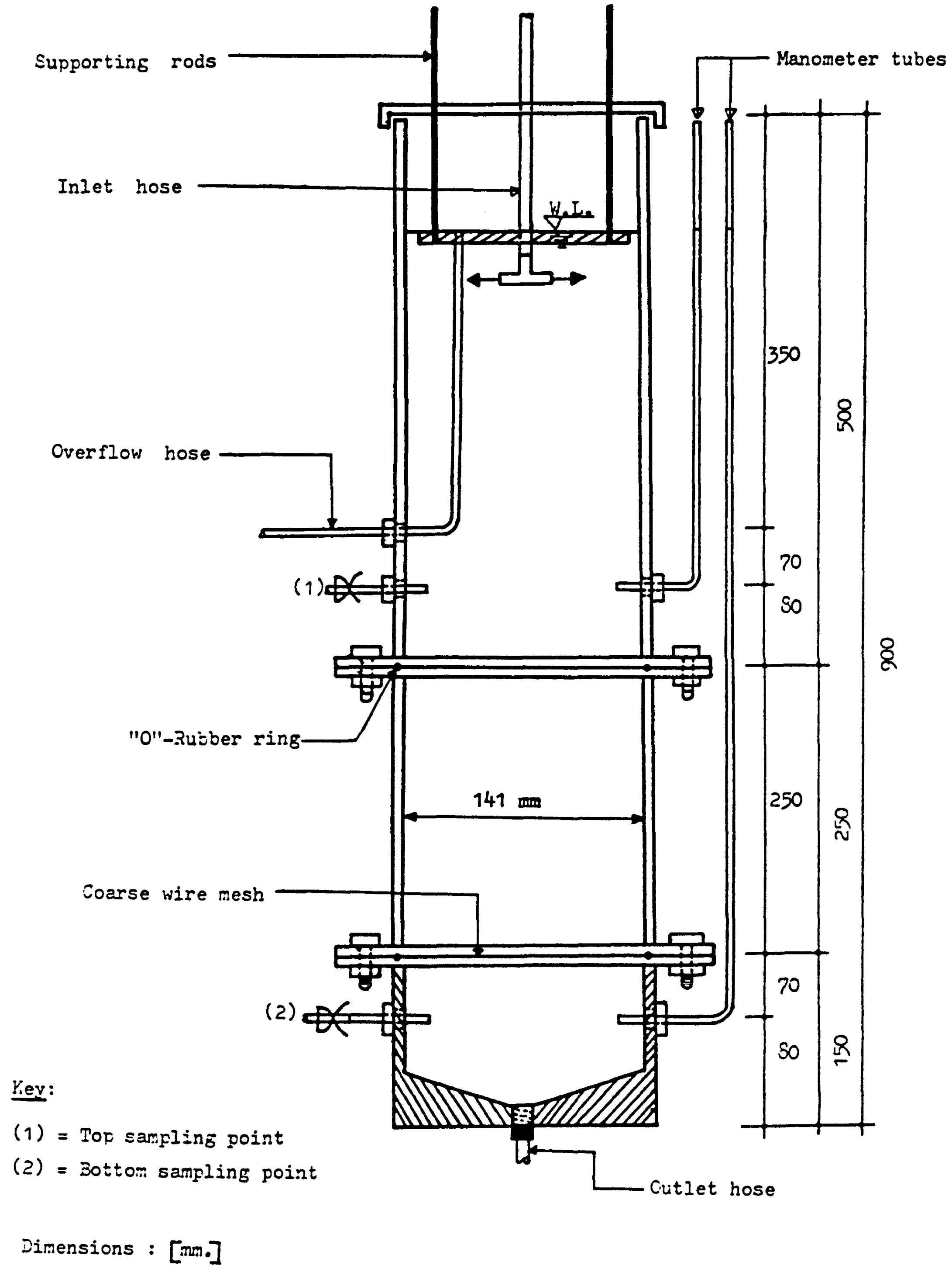


Fig. 3.4 The Permeability / Filtration Column .

investigation was supported on a single layer of coarse stainless steel screens (12x12, BS:gauge 24, ref.112) on its own or in conjunction with one layer of fine stainless steel screens (42x42, BS:gauge 34, ref. 112) when SSF sand was investigated. The screens were fixed in position at the bottom flanged connection. The supporting rods allowed variation of the position of the inlet hose and the overflow tube. The column was provided with two manometer tubes, one connected upstream and the other downstream of the stainless steel screens.

3.4 Permeability Experiments

The mains water which is continually filtered and recirculated in the hydraulics laboratory was fed into the perspex column (see plate.13) by a model 60-128 WB peristaltic tube pump (Glen Creston, Middlesex, UK) with an 190 Watt D.C. shunt motor connected to a thyristor speed controller (M.R. supplies, London). The mean characteristics of the mains water during the experiments are given in table. 3.2 . This water was augmented with London tap water (for characteristics see ref. 113) from time to time in order to maintain the level in the sump.

The cleaned fabrics had been soaked in de-ionized water for at least 24 hours prior to placement in the column. A number of multi-layered fabric thicknesses were set in the column and analyzed in turn. In each case, the column was

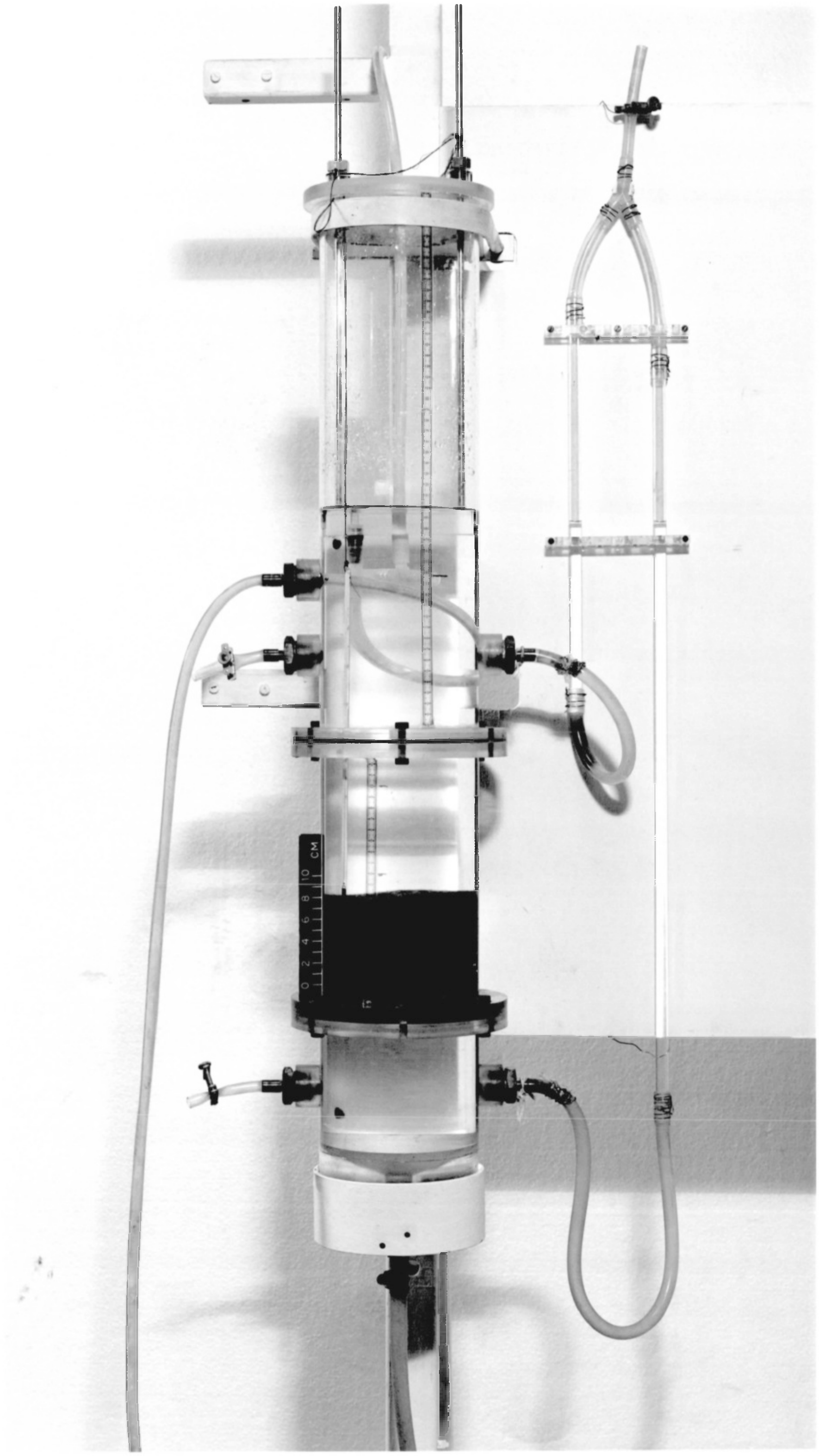


Plate.13 The Permeability Column .

Table 3.2 Mean Characteristics of Water

Parameter	Units	Mean	Observed range
pH	-	8.5	8.7 - 8.3
Turbidity	NTU	0.33	0.45 - 0.26
Elect. Cond.	μmhos/cm	769	850 - 670
Temperature	^{o}C	18.9	20.0 - 15.0

filled with water to a level of about 150 mm above the screens prior to placing each fabric layer individually in order to reduce the chances of air entrainment. Each layer was placed evenly to ensure a close fit between fabrics and the walls and without undue pressure in order to ensure no influence on fabrics total thickness. The water was then allowed to flow through the fabrics via a Platon (Platon Flow bits, Basingtoke, UK) flow meter which was used to control the filtration velocity. After about 5 minutes of flow stabilization, the head loss across the fabric was measured at five approach velocities in the range of 0.1 - 1.0 m/h, with a Telescope (Precision Tool & Instr. Co., surrey, UK) provided with a vernier gauge of an accuracy of 0.01 mm .

Four or three different multi-layered fabric thickness were evaluated in this way for all fourteen fabrics tested and the SSF sand. Prior to placement of any filter media in the column, the head loss across the screens alone were determined in a similar manner in order to allow evaluation of the true fabric head losses. Plate.14 shows the overall layout of the rig with water being pumped from the white

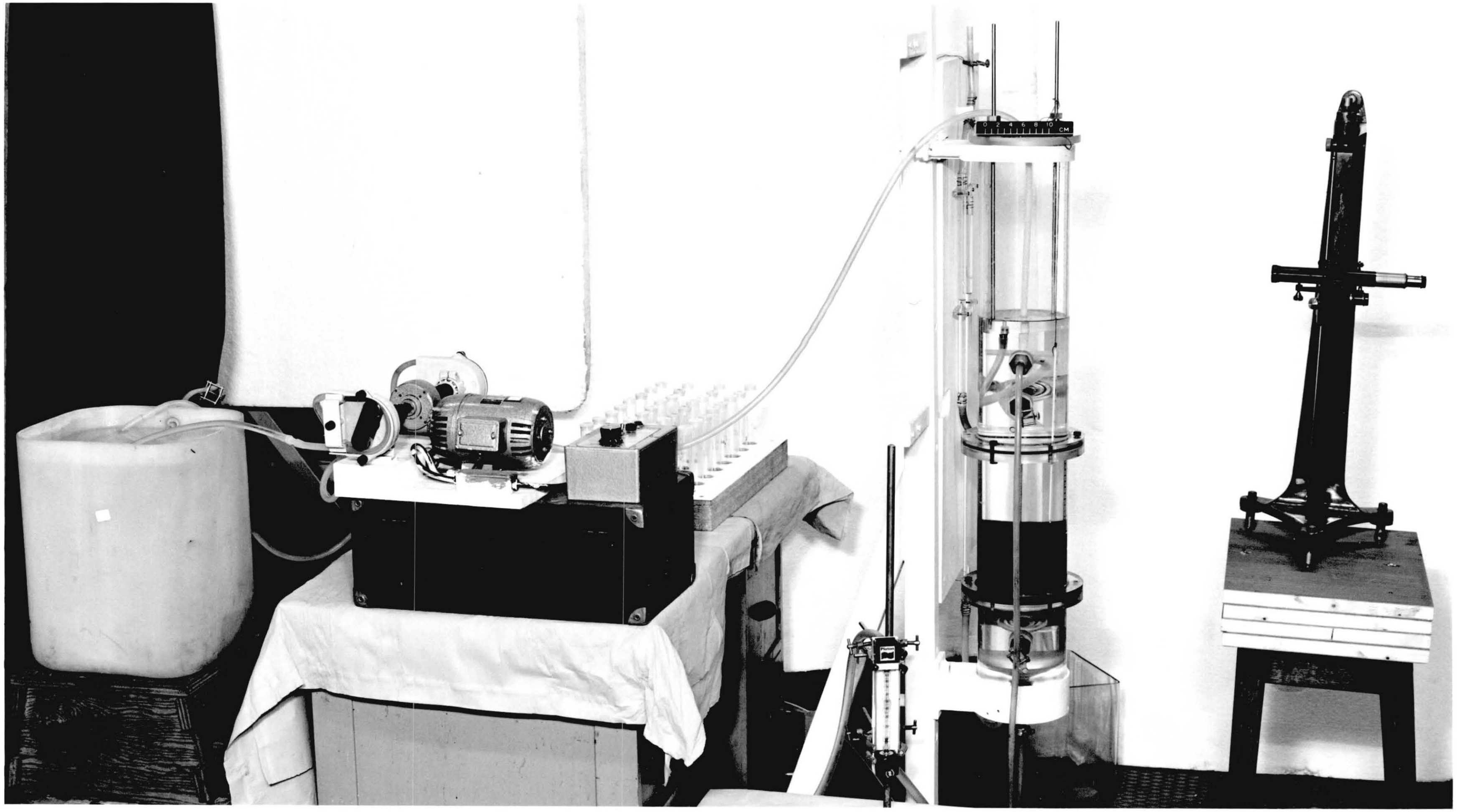


Plate.14 The Set-Up of Permeability Experiments.

polythene tank on the left. During the experiments, the temperature of water in the column ranged from 17.0 - 20.0 degrees centigrade except for fabric lab. No. 27 which was evaluated later when the water temperature was 21.7 ^{o}C.

The most porous fabrics (i.e. lab. Nos. 32 and 61) had to be handled with exceptional care due to their high compressibility while placing in the column. This was necessary in order to avoid or minimize any influence on total fabric thickness. Another difficulty with these fabrics was their inability to register any headloss at flow velocities of less than 0.5 m/h . For these two NWF, it was decided to increase the headloss evaluation velocity range to 0.5 - 2.0 m/h in order to register more readable headlosses by the telescope, nevertheless, the readings were still very low. The total depth of multi-layered fabrics was measured with a screw depth gauge (manufactured at Imperial College, accuracy ± 0.01 mm) within the perspex column immediately after placement of the fabrics. The maximum time of headloss analysis for each fabric thickness at five velocities of approach was limited to one hour in order to avoid excessive formation of air bubbles in the column.

Although literature (114,115) suggests the use of de-aired water with a maximum of 6 ppm dissolved Oxygen for permeability experiments in geotextile applications, such an approach was considered to be time consuming. If the intention was simply to compare the permeabilities as indices then the use of de-aired water may probably have been justified. To assess reproducibility of the results of this experiment, fabric lab. No. 45 was analyzed twice with similar multi-layer fabric thicknesses.

3.4.1 Results

Figs. 3.5 through 3.8 show the relationship between headloss and fabric thickness for some of the fabrics analyzed and SSF sand at approach velocities ranging from 0.10 - 1.0 m/h. The graphs show a linear relationship with increasing headloss for all the five approach velocities thus proving that the filter media were fairly uniform in nature. However, for fabrics lab. Nos. 32 and 61 which were evaluated at higher velocities, the results of such plots were nearly linear at 0.5 m/h only.

The mean hydraulic gradients $i = \Delta H/ L$ of each fabric at different approach velocities were evaluated and plotted as indicated in Figs. 3.9 through 3.17, Compliance with Darcy's law should result in a linear relationship. From the observed results, with exception of the fabrics lab. No. 32 and 61, the graphs show a linear relationship which allows evaluation of hydraulic conductivity from the gradients of the resulting lines. These are given in table 3.3 for NWF and the SSF sand. Repeatability experiments results for lab. No. 45 indicated on Fig. 3.9 proved that

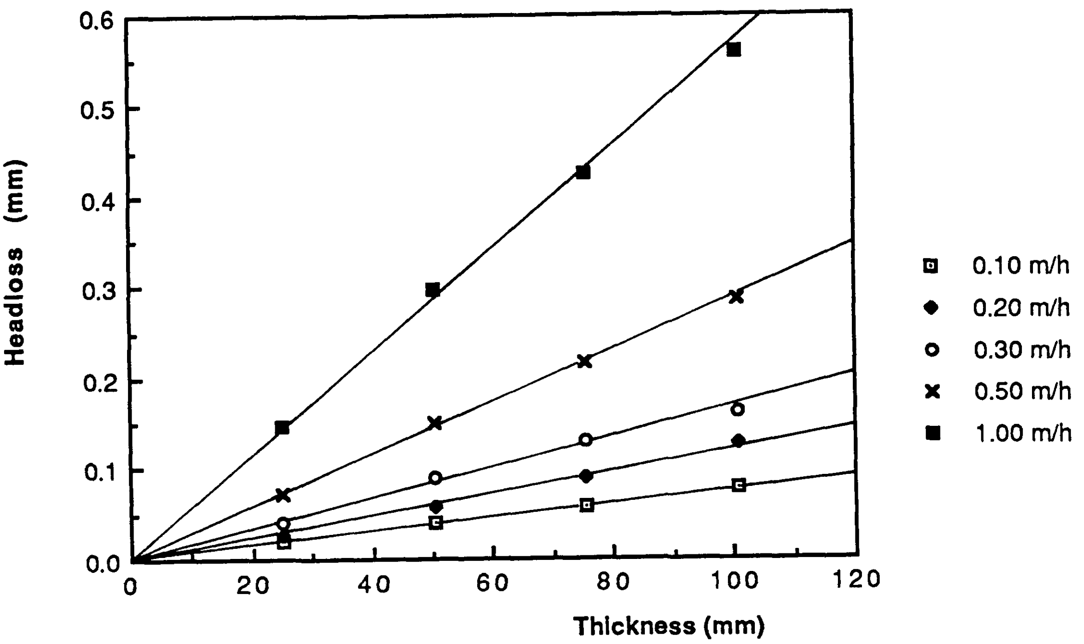


Fig. 3. 5 Head Loss Pattern in Lab. No. 27 ·

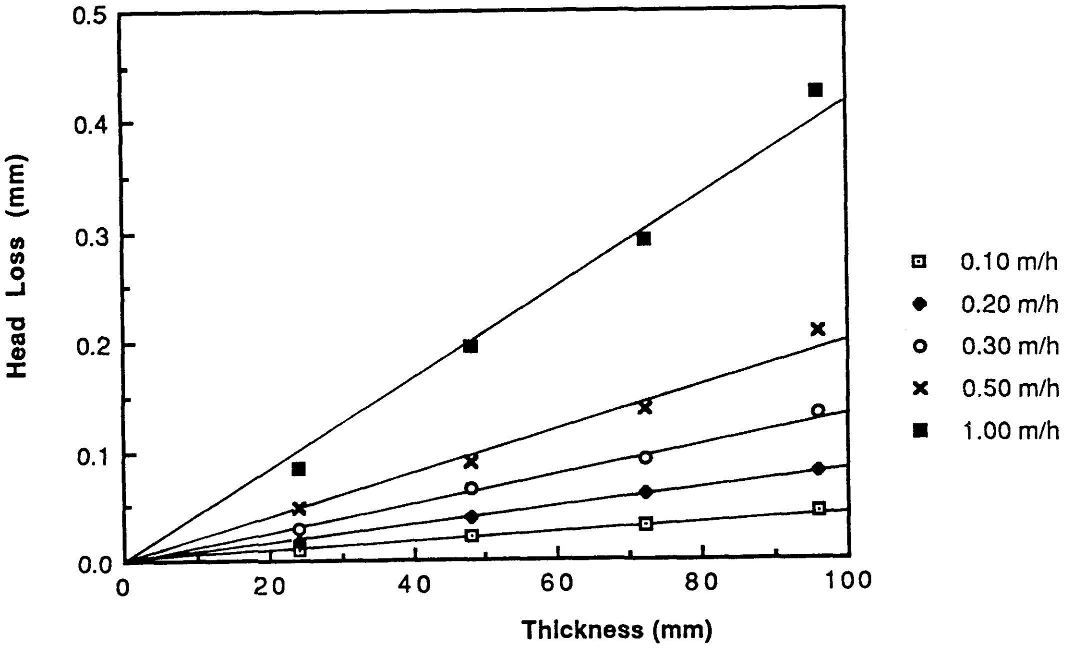


Fig. 3. 6 Head Loss Pattern in Lab. No. 28 ·

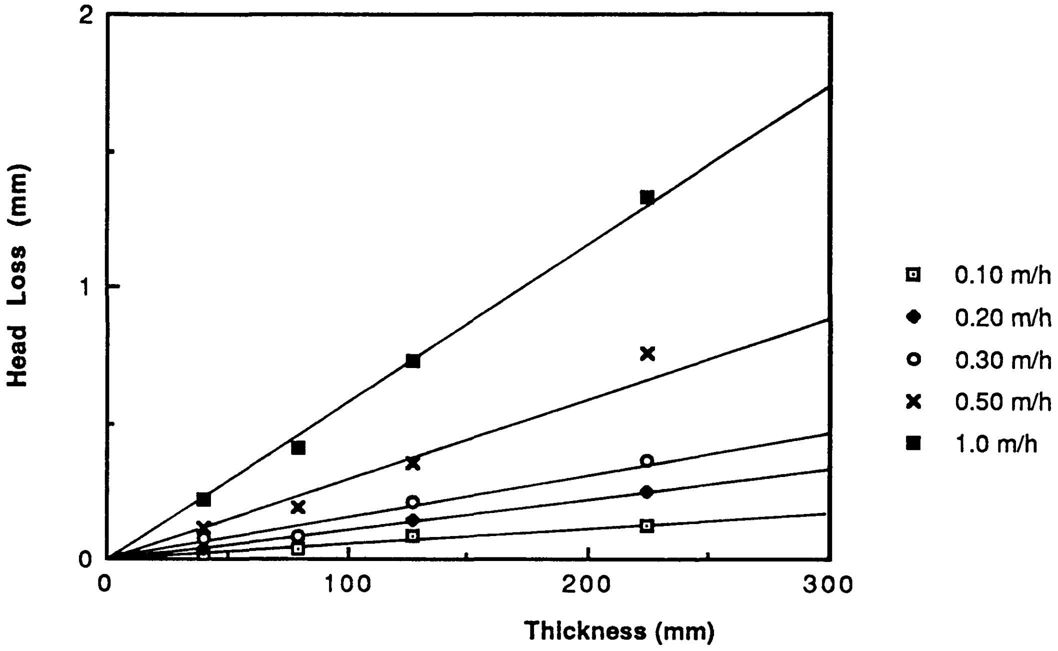


Fig. 3. 7 Head Loss Pattern in Lab. No. 45 ·

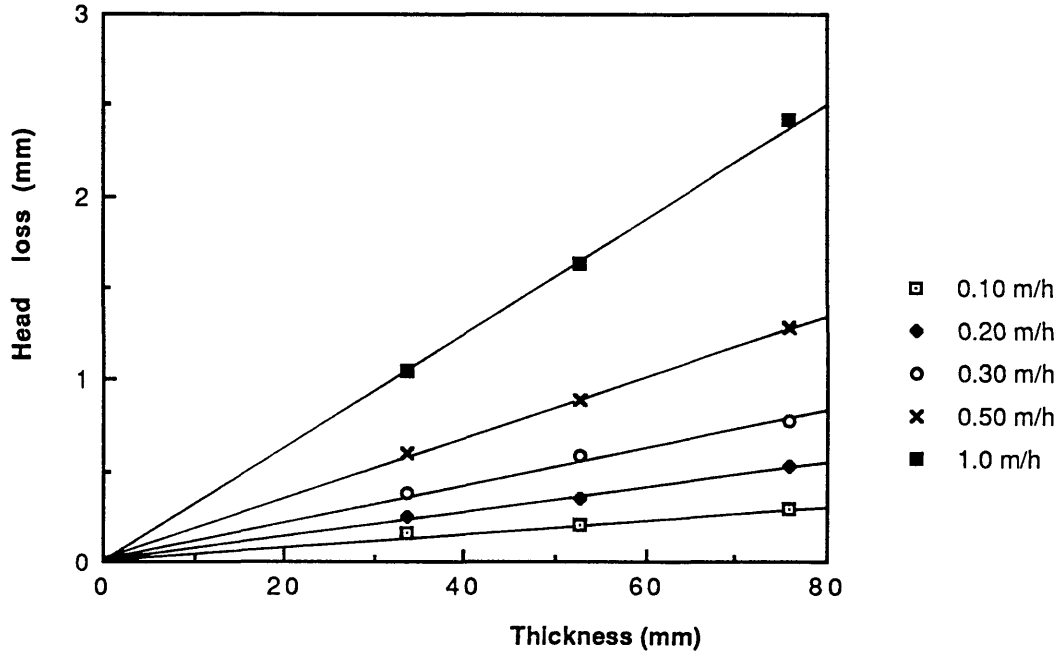


Fig. 3. 8 Head Loss pattern in SSF sand ·

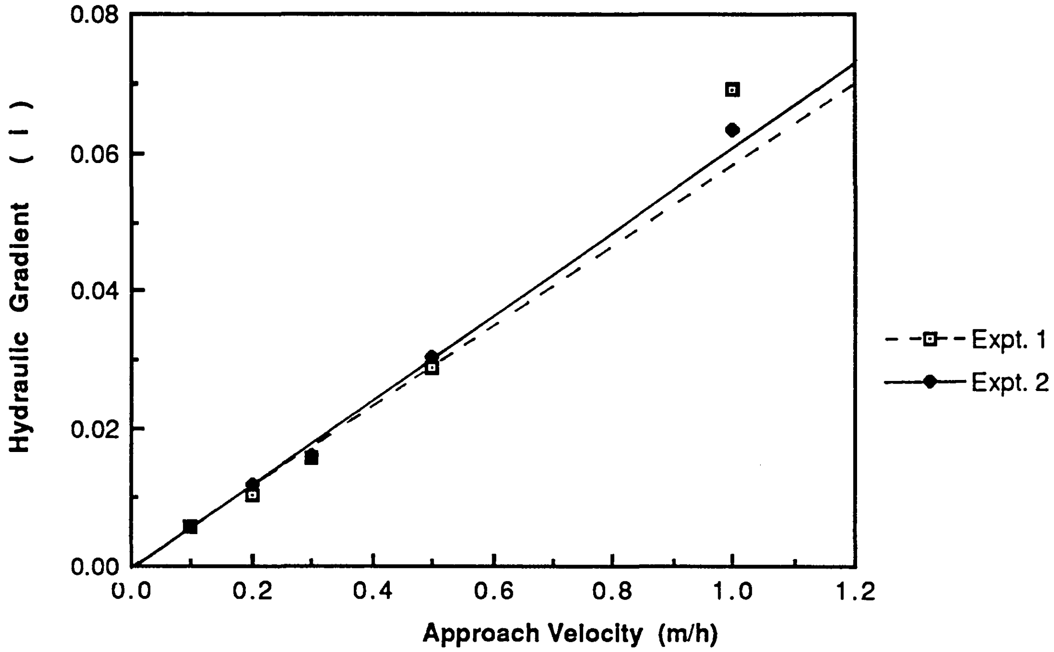


Fig. 3. 9 Repeatability of Hydraulic Characteristics of Lab. No. 45 .

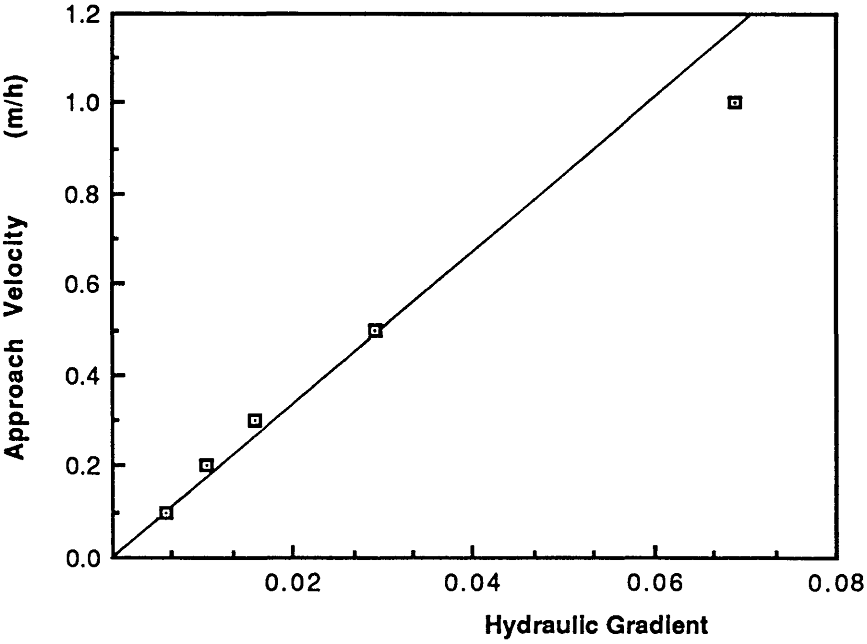


Fig. 3. 10 Hydraulic Characteristics of Lab. No. 45 .

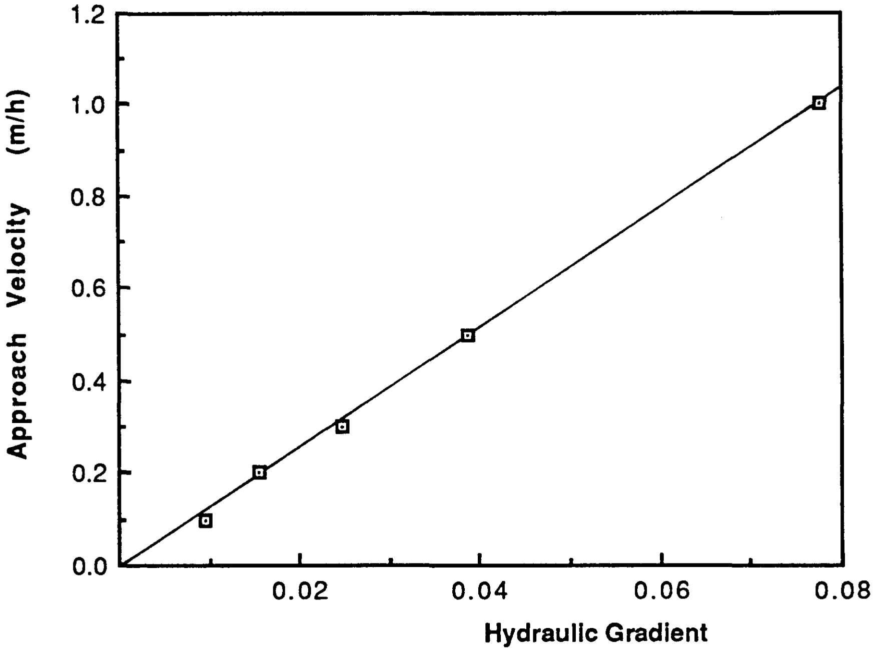


Fig. 3. 11 Hydraulic Characteristics of Lab. No. 27 .

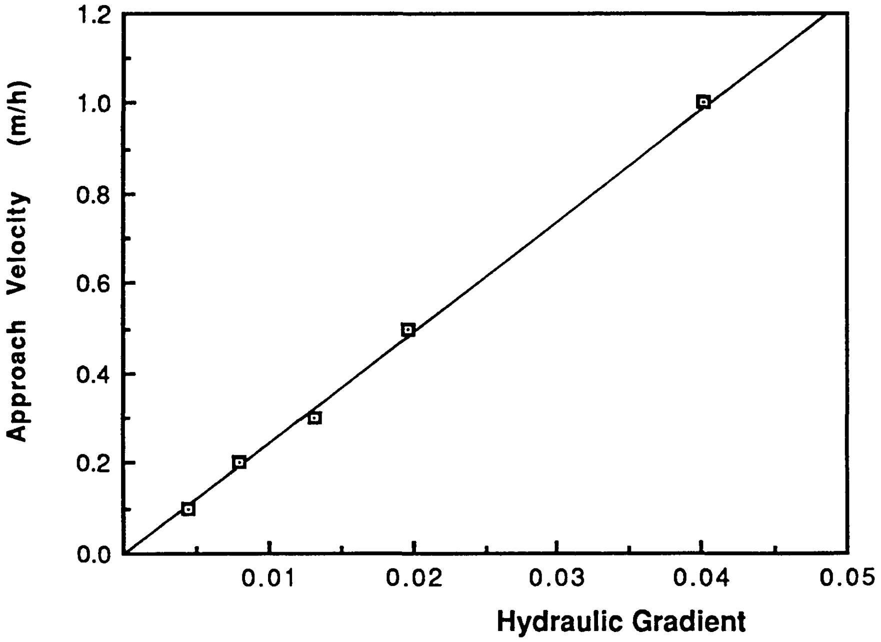


Fig. 3. 12 Hydraulic Characteristics of Lab. No. 28 .

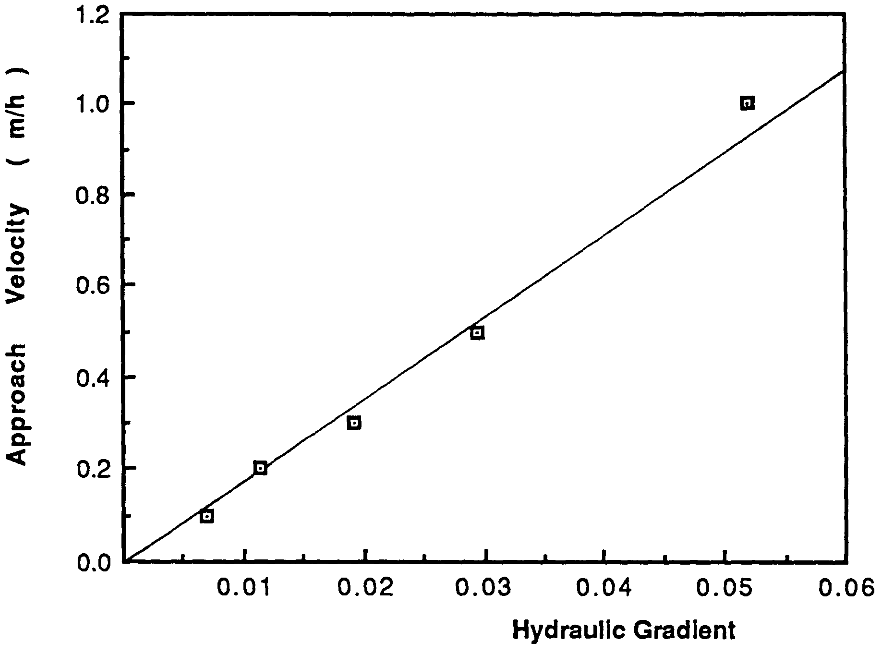


Fig. 3. 13 Hydraulic Characteristics of Lab. No. 26·

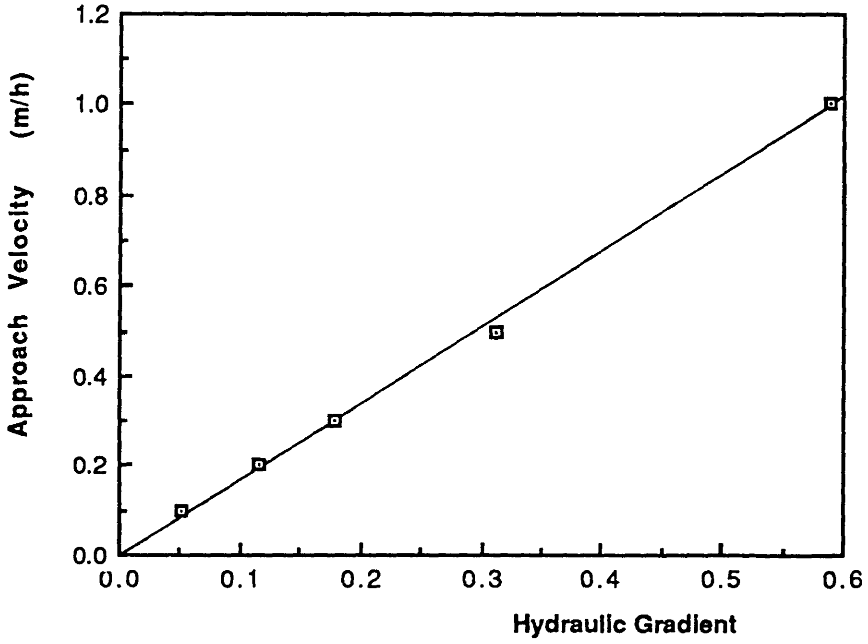


Fig. 3. 14 Hydraulic Characteristics of Lab. No. 44 .

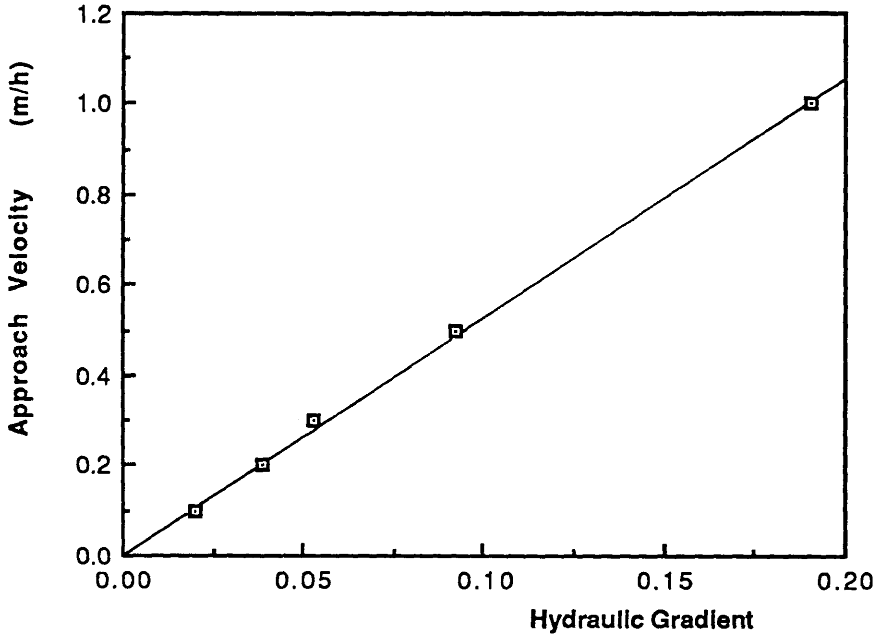


Fig. 3. 15 Hydraulic Characteristics of Lab. No. 55 .

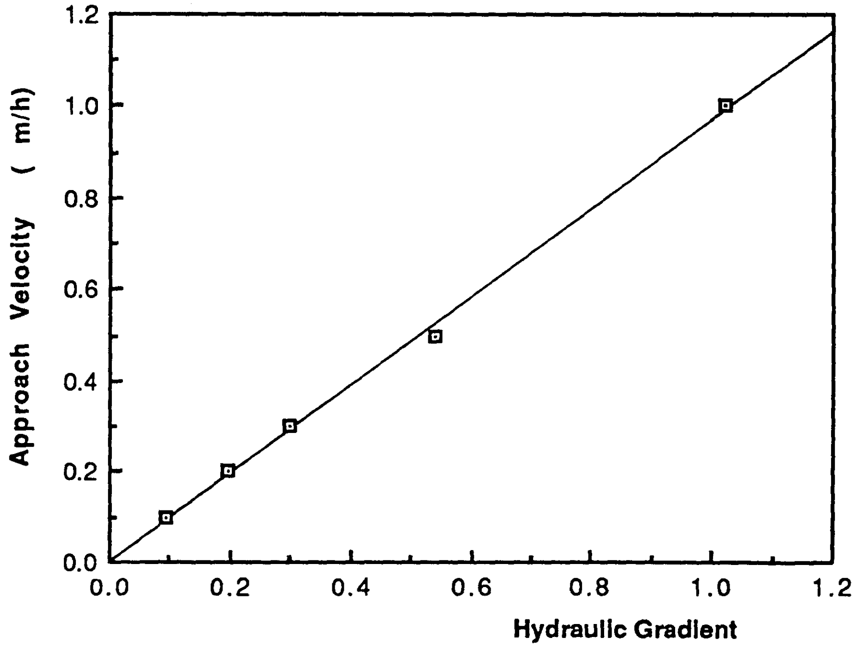


Fig. 3. 16 Hydraulic Characteristics of Lab. No. 80 .

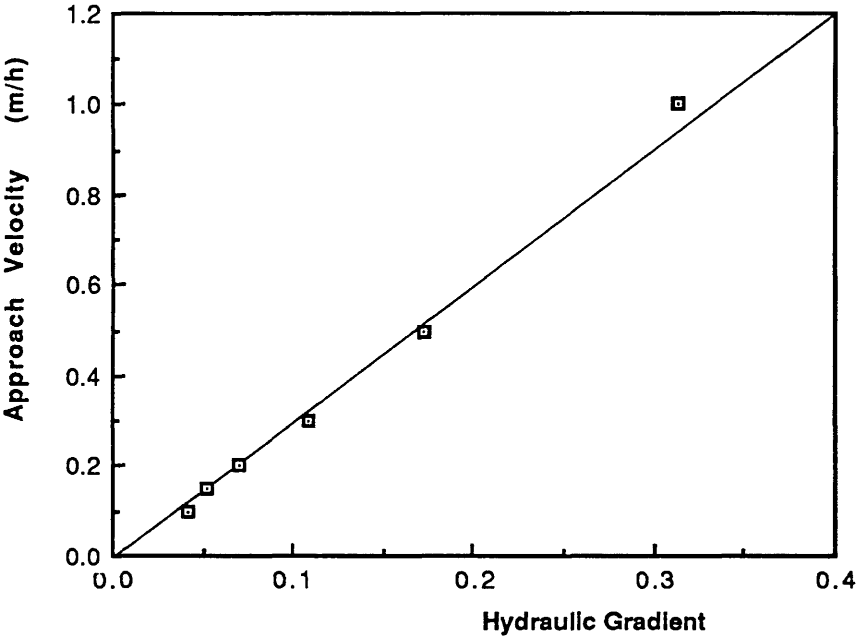


Fig. 3. 17 Hydraulic Characteristics of SSF Sand.

the results were reasonably reproducible. For this fabric, the mean hydraulic characteristics is given in Fig. 3.10 . As regards fabric lab Nos. 32 and 61, the values of hydraulic conductivity quoted in table 3.3 correspond to an approach velocity of 0.5 m/h only.

Table 3.3 Hydraulic Conductivity of Filter Media

Fabric Lab. No.	Hydraulic Conductivity mm/s
80	0.25
44	0.49
55	1.51
11	4.4
26	4.8
27	4.8
45	4.9
57	5.6
13	5.8
25	6.1
28	6.9
21	11.1
61	33.0*
32	47.0*
Sand	0.84

* At an approach velocity of 0.5 m/h only.

3.4.2 Discussion of Results

A comparison of tables 1.2 and 3.3 shows that permeability results are in reasonable conformity with the findings of Masounave et al (95) who showed that permeability of NWF is inversely proportional to fabric density which is in turn directly related to the specific surface. Other factors which influence the permeability are surface finish properties, fibre diameter and fibre/fabric(s) bonding techniques. Clearly dense heat bonded NWF are much less permeable than most needle-felted fabrics. There is some direct correlation between porosity and permeability although in this respect difficulties in experimental determination of hydraulic conductivities of the most porous NWF (i.e.ϵ_o > 96%) were met. It has already been mentioned in the preceding chapters that the Carman-Kozeny model is not suitable for theoretical description of hydraulic conductivity of NWF.

To assess the suitability of cell models and in particular Happel's model (97) in describing the permeability of NWF, theoretical values of permeability factor (k_h, m^2) given in equation **(29)** for fibre diameters of 30, 40 and 50 μ m are compared with the experimental results from table 3.3 in Fig. 3.18 . The results show a good correlation between experimental findings and theoretically determined predictions . In general, with exception of fabrics lab No. 44 and 80, all the NWF tested had higher permeability than SSF sand. However, from table 1.2 it can be seen that these two NWF were among the three fabrics with the highest specific surface area.

3.5 Filterability Experiments

Filterability experiments were carried out with the perspex column used for permeability experiments modified to exclude the middle flanged portion as indicated on plate.

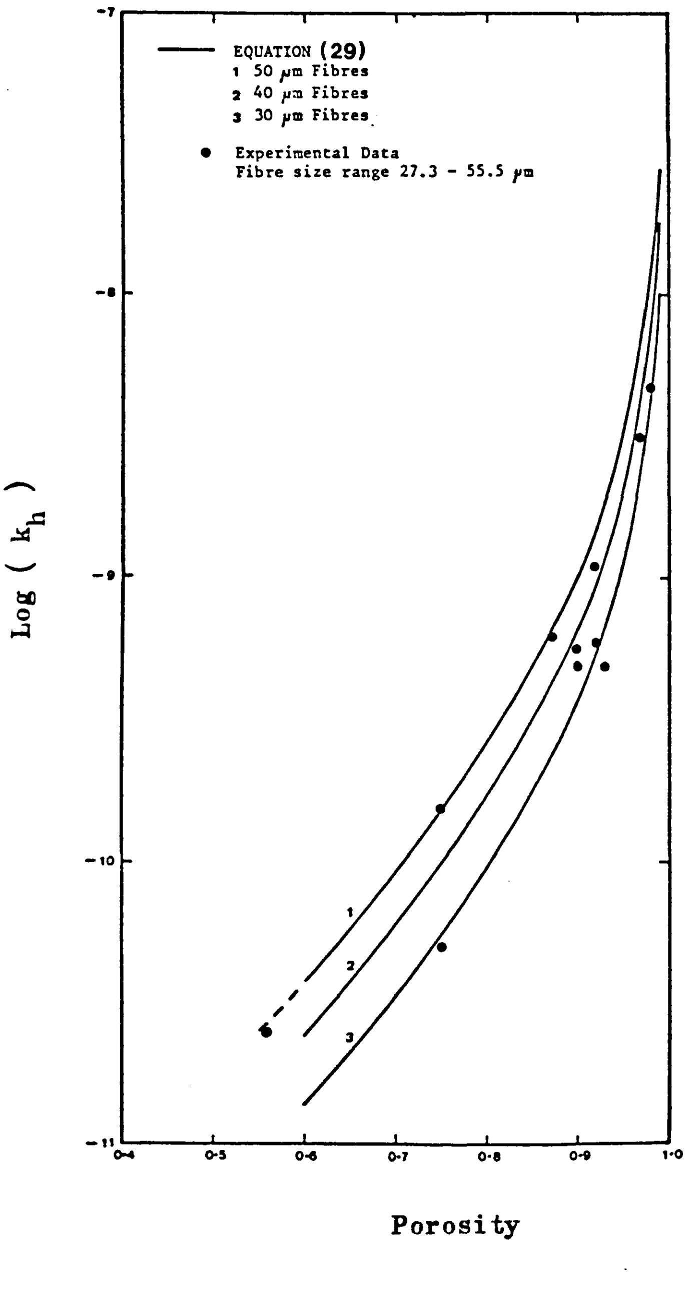


Fig. 3.18 Theoretical and Experimental Relationship Between Permeability Factor (k_h, m^2) and Porosity of NWF.

15. The experiments were carried out in order to compare the clean bed filter coefficients of the filter media (table 3.4) on the basis of the relationship given in eguation **(5)** where upon re-arrangement and consideration of λ_o in place of λ, the following relationship is obtained:

$$\lambda_o = \mathrm{Ln}\ (C_o/C_e)\ /\ L \qquad \textbf{(41)}$$

Prior to carrying out any filtration experiments, a number of preliminary tests were done in order to calibrate the column and the suspension.

3.5.1 Preliminary Tests

The purpose of carrying out the tracer test was to establish the hydraulic efficiency of the filter column. Since the experiment was planned to use electrical conductivity of NaCl solution as the tracer parameter, a calibration of NaCl concentration by weight (%) against electrical conductivity (m mhos/cm) measured by a model MC-1, Mark V electrolytic conductivity cell (Electronic Switchgear, London) was done. For this purpose, different quantities of analar grade NaCl (BDH, UK) were weighed on an Oertling R42, Mark II balance, accuracy ± 0.3 mg (Oertling Ltd. , Orpington, UK) and dissolved in pre-measured volumes of de-ionized water to make NaCl solutions of concentration (by weight) ranging from 0.1 - 4.0 % .

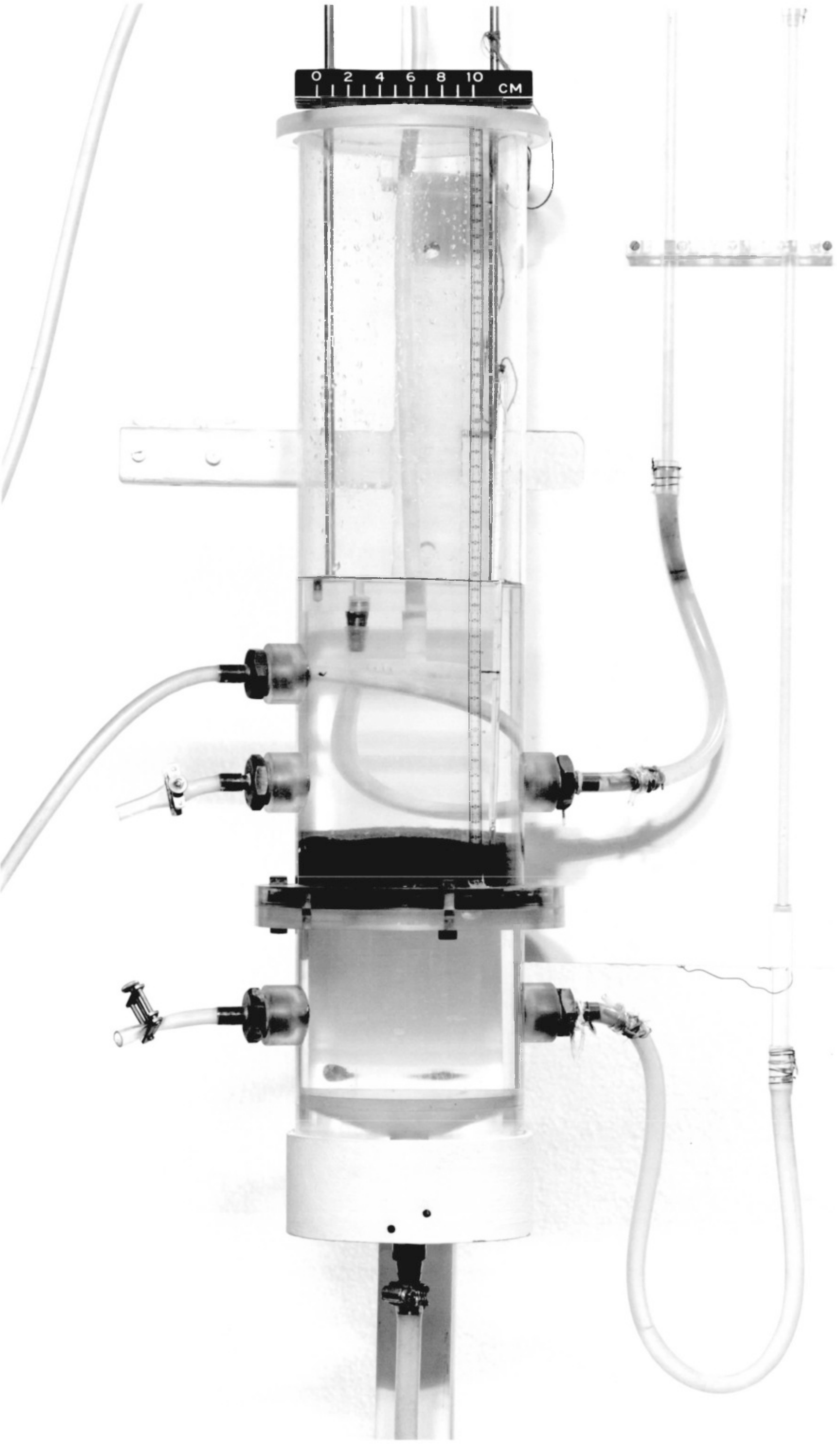


Plate.15 The Filtration Column.

For each concentration, three samples were measured separately to obtain the corresponding average electrical conductivity. The average electrical conductivity of de-ionized water was found to be 39.5 μ mhos/cm contributing just about 2% at the lowest concentration used (i.e. 0.1% NaCl). Corresponding corrections were made to the conductivity values at different concentrations. The results of this experiment as measured in the lab. and corrected for reporting at 25 ^{o} C are presented on Fig. 3.19. The NaCl concentration - Conductivity relationship was found to be linear thus showing a direct proportionality of the two parameters. This observation justified the use of electrical conductivity as an indirect measure of NaCl strength. Weast et al (112) present an almost similar relationship for the range of NaCl concentration analyzed during this study.

After calibration of NaCl concentration (%) to electrical conductivity, a tracer test experiment was done with a 4% solution at an approach velocity of 0.3 m/h . In order to establish the time which had to be allowed to elapse before taking any effluent samples at the start of filtration experiments, the minimum residence time had to be noted when the electric conductivity of the inlet and filtrate sampling point in the column were equal. For this experiment, average filtration conditions were considered and therefore six layers of an intermediate fabric lab· No. 26 were placed on top of the screens and the inlet hoses were set at a height of 80 mm above the top fabric level.

Upon considering the fabric effective velocity, at 0.3 m/h, a theoretical minimum residence time of 36.2 minutes for 100% tracer concentration at the filtrate sampling point was estimated. However, Fig. 3.20 gives the results of the tracer experiment which showed that the actual observed minimum residence time was 38 minutes. For the approach velocity of 1.0 m/h a theoretical residence time of about 11 minutes was estimated and the observed minimum residence time was 12 minutes. The residence times at both approach velocities allowed for the travel time through the inlet tube immediately after switching the pump on.

3.5.2 Filter Media and Suspension Characteristics

3.5.2.1 Filtration Filter Media

Table 3.4 gives the list of NWF selected for filtration experiments. It can be seen that the NWF were selected so as to cover a wide range of porosity, specific surface, manufacturing techniques and also to compare the performance of fabrics with similar properties, production techniques and also supplied by the same manufacturer.

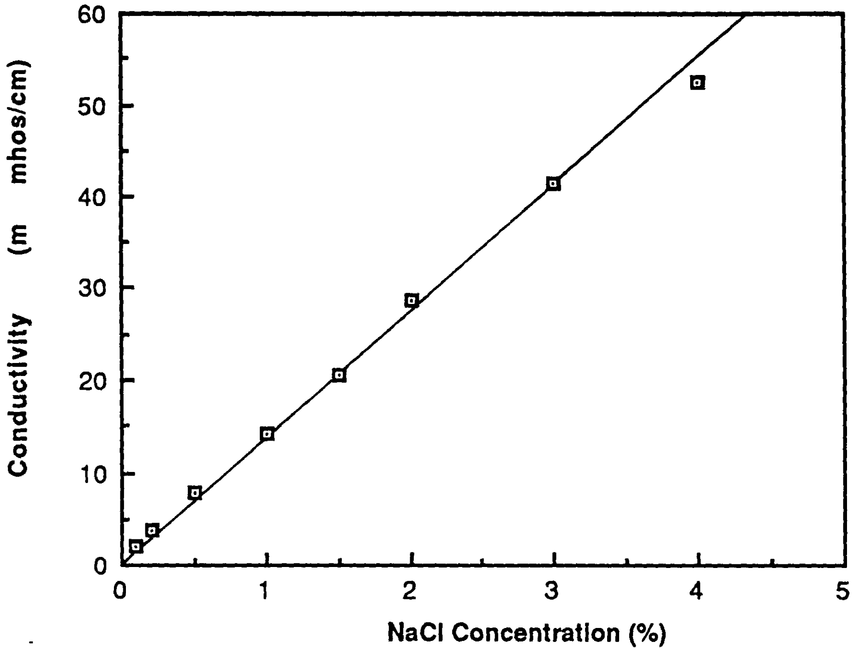


Fig. 3.19 Nacl - Conductivity Calibration.

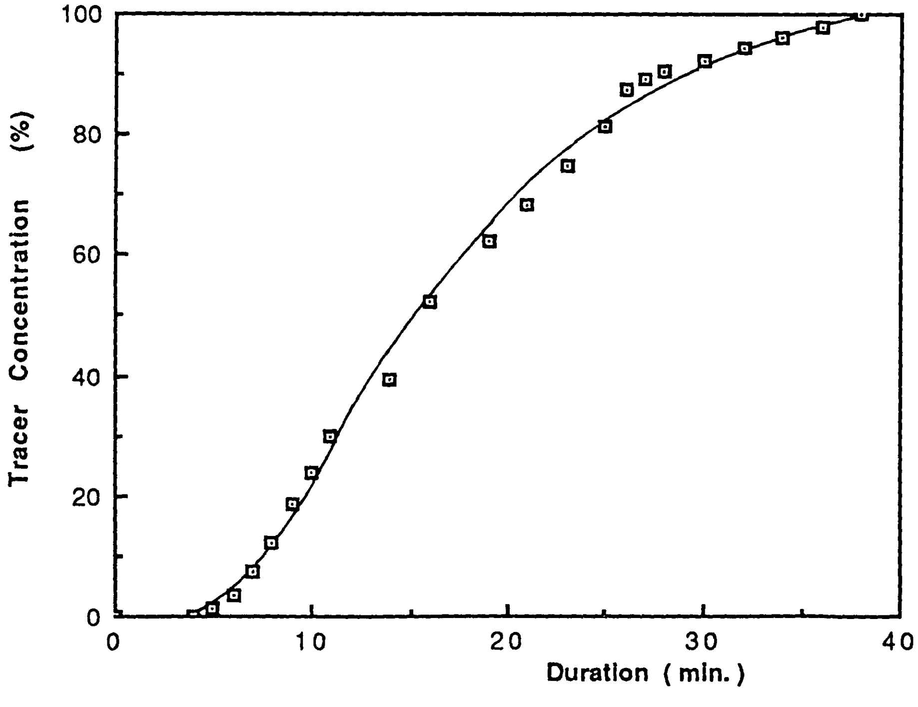


Fig. 3. 20 4 % NaCl Tracer Test for the Filtration Column , 0.3 m/h .

Table 3.4 Filtration Experiments Filter Media

Fabric Lab.No.	Production Technique	d_f (μ m)	ϵ_o (%)	S (m^2/m^3)
32	RSPB	50/40/40	98	1, 671
25	NF - CT	48	87	10, 609
11	NF - SB	27.3	93	10, 620
26	NF - CT	48/100	80	10, 833
28	NF - CT	33	89	13, 266
27	NF - CT	33	88	14, 431
55	TB	40	75	20, 300
44	NF - TB	27.9/30.5/41.4	75	33, 238
sand	-	d_{10}=0.3 mm	-	12, 600

Assume $\phi = 0.95$ and $\epsilon_o = 0.40$ for sand.

Legend:

RSBP = Resin spray bonded.
NF-CT = Needle-felted-spunbonded.
NF-CT = Needle-felted on carrier thread.
NF-TB = Needle-felted-thermic bonded
TB = Thermic bonded.

3.5.2.2 Suspension Characteristics

Poly-disperse suspensions were prepared using commercial kaolin (China clay, Hopkins & Williams, UK) obtained as a fine powder with a chemical content reported previously (113). Fig. 3.21 gives the particle size distribution of kaolin as analyzed by the multiple tube technique with 50, 140, 280 and 400 μ m orifice diameter tubes on a model TA II Coulter counter (Coulter Electronics Ltd. , Luton, UK).

The standard saline-based Isoton II solution (Coulter Electronics Ltd., UK) was used as an electrolyte. A small amount of ultra-sonically dispersed kaolin slurry was

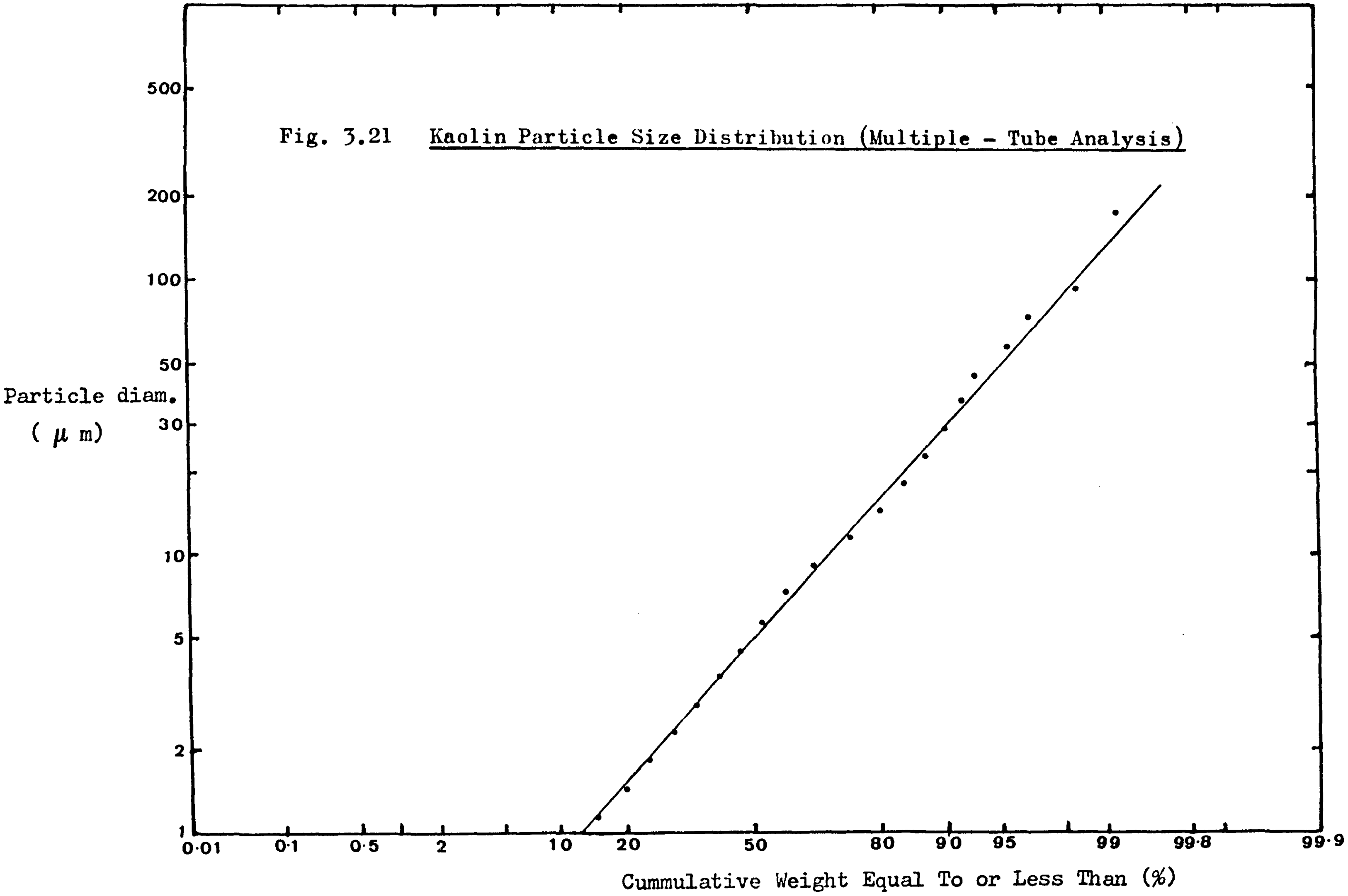


Fig. 3.21 Kaolin Particle Size Distribution (Multiple - Tube Analysis)

prepared using Isoton II. After setting the calibration knob and matching switch appropriately, the multiple-tube analysis was done in the manner described elsewhere (116) and the results were combined to cover the whole range of particle sizes (i.e. 1 - 160 μ m).

Assumption of conformity to Log-Normal probability distribution allowed extrapolation of incremental volume distributions for diameters smaller than 1 μ m. Fig. 3.22 gives the cummulative particle size distribution for the four tube analysis. It must be noted that the corresponding equivalent volume diameters used are the average of the upper and lower edges of all channels considered. Furthermore, literature (113) suggests that kaolin has a negative overall zeta potential in natural waters.

A further preliminary experiment which was done was correlation of turbidity (NTU) with the gravimetric concentration of kaolin suspensions (mg/l). The intention was to establish the relationship between turbidity and gravimetric concentration of kaolin . Such a correlation can be used in determination of the ultimate specific deposits (σ_u) of the filter media if the density and the compaction coefficient of deposited kaolin is known. A number of suspension concentrations were duplicated in order to get a general trend of the correlation. The results showed that the relationship was linear for kaolin concentrations not exceeding 200 mg/l, this corresponded to a maximum turbidity of 125 NTU. Fig. 3.23 depicts the correlation for the range of concentration covered which was from 10 to 500 mg/l . Higher suspension concentrations were found to result in light extinction due to excessive settling of particles (probably of non-discrete nature) . Contrary to the experimental findings of Champion (117) and Demby (118) but in reasonable conformity with Graham (113), in the linear range it was found that 1 NTU corresponded to approximately 1.6 mg/l .

3.5.3 Experimental Procedures

The clean bed filter coefficients of the filter media listed in table 3.4 were evaluated on the basis of comparison of particle size analysis of inlet suspensions and filtrates. Three grams of kaolin powder were added to 100 ml de-ionized water in a beaker and ultra-sonically dispersed for five minutes prior to being magnetically stirred for a further five minutes. Then the dispersed solution was diluted in 40 litres of mains water to make a concentration of about 75 mg/l corresponding to a turbidity of 40 NTU. Both the overhead dosing tank and the filtration column were operated at constant heads . While the overhead dosing tank was continually stirred with a magnetic stirrer, the main suspension container was provided with a continually operated motorized stirrer.

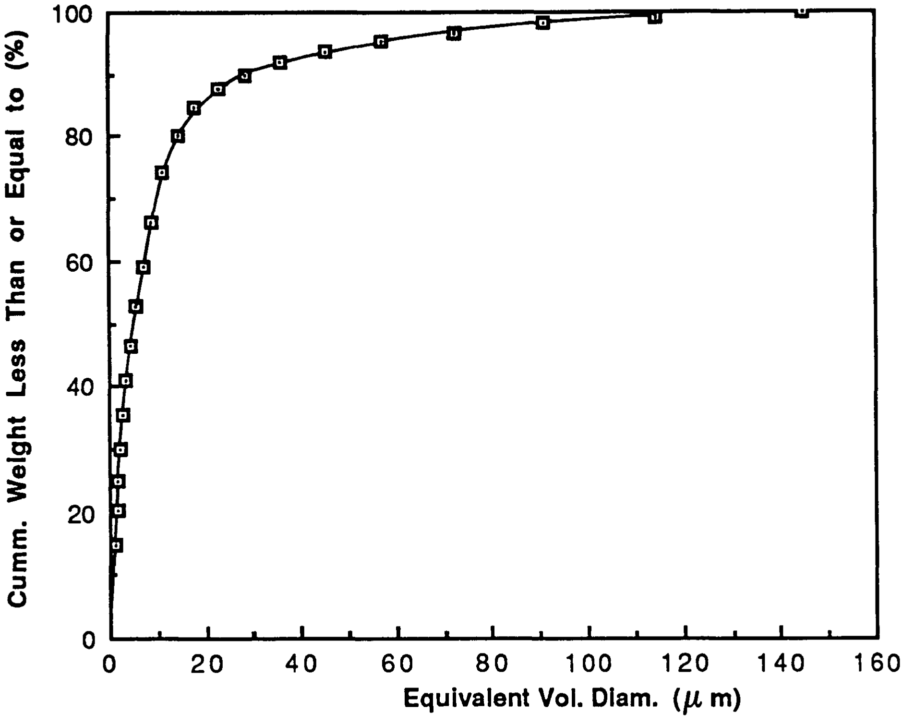


Fig. 3. 22 Kaolin Particle Size Distribution ·

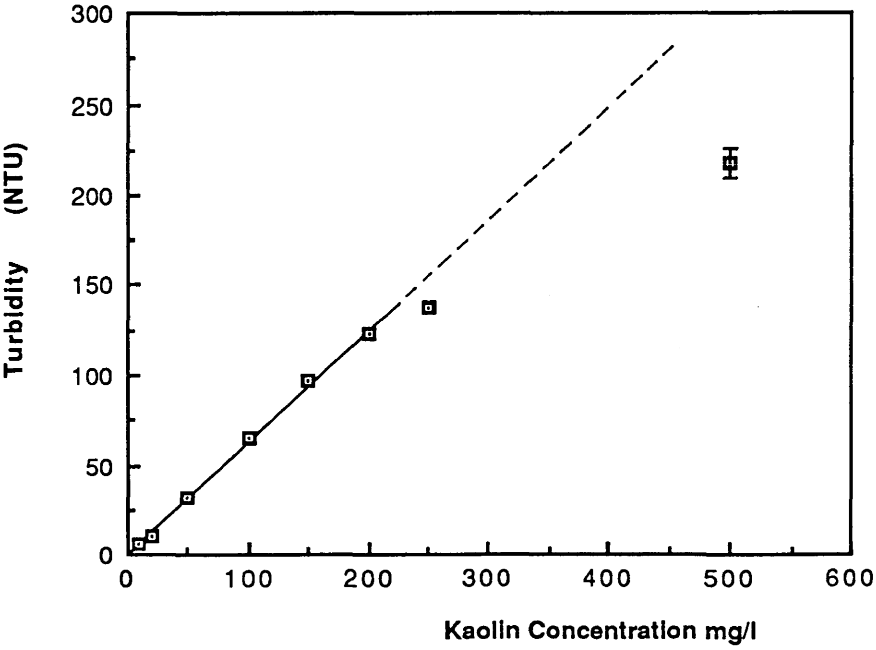


Fig. 3.23 Turbidity - Kaolin Concentration Callibration.

Fig. 3.24 gives the schematic flow scheme of this experimental set up while plate.16 shows the set up without the over-head tank. Recirculation of over - flows made it possible to keep variations of inlet suspension turbidity to within 2-3 units during the experiments. Turbidity was monitored in order to control the stability of the inlet suspension only. This parameter was analyzed as Nephelometric Turbidity Units (NTU) on a model 2100A Hach turbidimeter (Camlab, UK). Three or four different multi-layered fabric thicknesses were analyzed. For each fabric (or sand) thickness, filtration experiments were carried out at approach velocities of 0.3 and 1.0 m/h .

Turbidity as well as particle size analysis of inlet suspension and filtrate samples were taken at each approach velocity. Again, three or four fabric multi-layer thicknesses were investigated in each case. At the begining of the experiments, inlet suspension and filtrate turbidity samples were taken from the column . Then the column was kept running for 40 or 15 minutes which were set as the standard minimum residence times at 0.3 and 1.0 m/h, respectively. Further inlet suspension turbidity samples were then taken on attainment of the residence time, 5 and 10 minutes later. Filtrate turbidity samples were taken at 5, 10 and 30 minutes after the applicable minimum residence time.

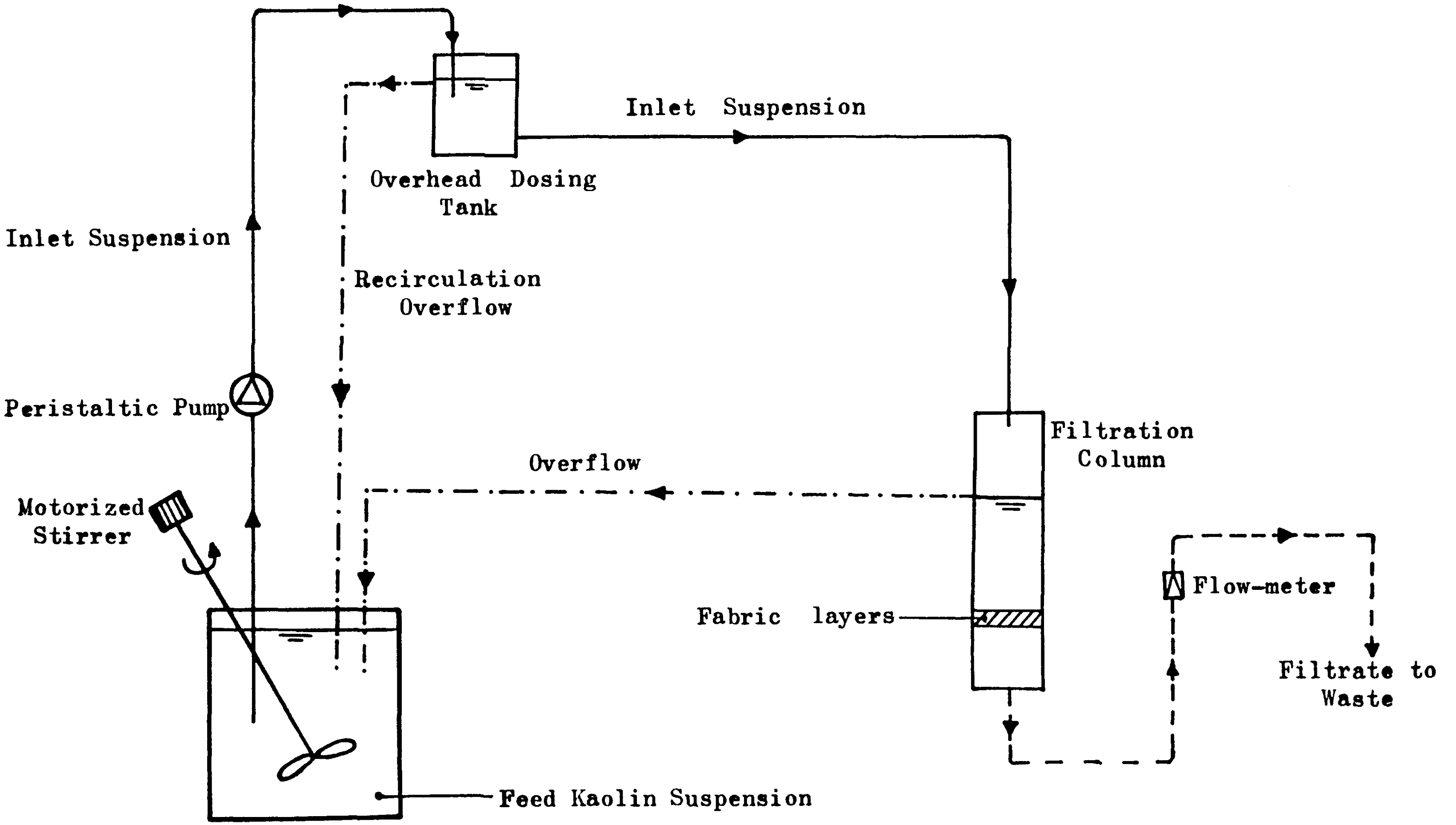


Fig. 3.24 Filtration Experiments Flow Scheme.

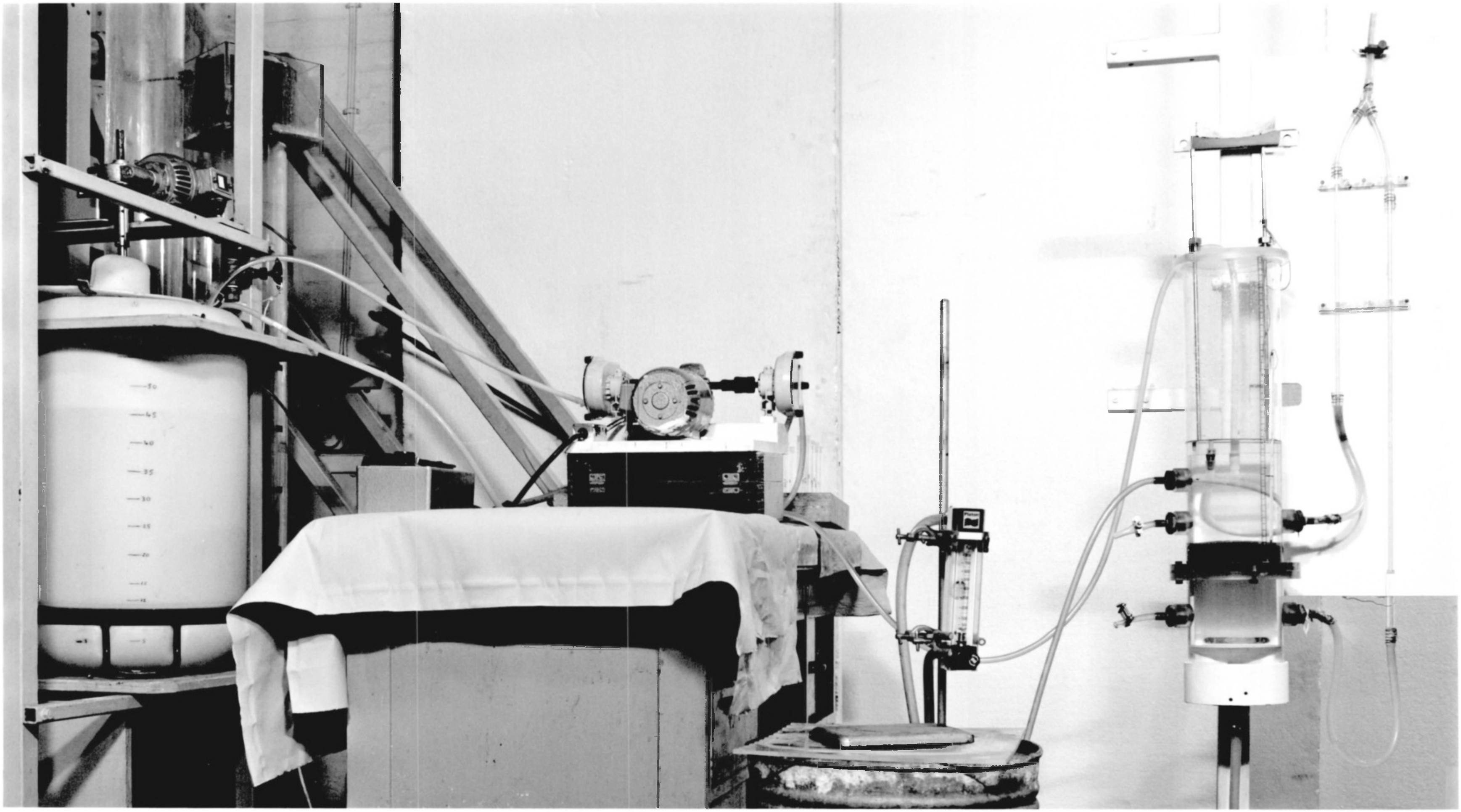


Plate.16 The Set-Up of Filtration Experiments.

50 ml samples of the inlet suspension were taken for particle size analysis at 10 and 15 minutes after the applicable minimum residence time. Similar volumes of filtrate suspensions also for particle size analysis were taken at 15 and 20 minutes after the applicable residence time. For each fabric, at one selected fabric thickness and an approach velocity of 1.0 m/h, the filtration experiments were triplicated in order to check reproducibility of the results. For sand, filtration triplication was done for a thickness of 20mm at both approach velocities (i.e. 0.3 and 1.0 m/h)

The particle size analysis samples were analysed on a Coulter counter with an 100 μm orifice diameter tube (see plate. 17). The saline-based Isoton II was used as an electrolyte. 160 ml of the electrolyte was filled in a beaker kept continually stirred in the sampling stand. After setting the calibration knob and matching switch positions appropriately, the sampling switch was set on the "time" mode and the preset counter at 100 seconds. For each inlet suspension or filtrate sample one analysis involving addition of 10 ml of the sample to 160 ml electrolyte was done in order to obtain the differential volume distribution.

The results for the two inlet and filtrate samples were separately averaged to obtain the volume distributions in

Plate.17 Model TA II Coulter Counter With Sampling Stand.

the inlet suspension and the filtrate. Since at that time no population counting accessory (PCA) was available, the number distributions for evaluation of the clean bed filtration coefficients were calculated from the raw incremental volumes on basis of the analysis suggested in literature (119). The method involves estimation of the number distribution from the arithmetic mean volume of the differential volumes and the total number count. In this case, the arithmetic average volume of the channel sizes at the two channel edges is taken as an approximation to the real average volume of the particle. The Computer programme list TS1 (attached as appendix.1) was used to evaluate the number counts in all the channels.

For every fabric and SSF sand, the overall mean fabric initial filter coefficients for different channels were statistically evaluated using the student's t - distribution . The equivalent volume particle diameters used were the averages of the lower and upper channel boundaries .

3.5.4 Results

A statistical survey of all fabrics investigated showed that the λ_o - variation (On the basis of the student's t-tests and the Relative Standard Deviation, RSD) for different thicknesses of the same fabric was not significant for kaolin particles in the range of 2.26 to

5.7 μ m only. For most fabric thicknesses, the validity extended to diameters of up to 7.18 μ m . At the approach velocity of 0.3 m/h, the SSF sand RSD ranged from 8.4 - 4.1 % , while for NWF the same ranged from 10.5 - 0.4 % . At the approach velocity of 1.0 m/h, the SSF sand RSD ranged from 8.4 - 3.3 %, while for NWF it ranged from 12.0 - 0.1%.

Table 3.5 gives the clean bed filtration coefficient for the eight fabrics and SSF for particles with average equivalent volume diameters of 2.26 - 7.18 μ m at the approach velocity of 0.3 m/h while table 3.6 gives the same at an approach velocity of 1.0 m/h. In conformity with conventional filtration theories (19,21), the fabric λ_o-values at 0.3 m/h are higher than at 1.0 m/h for the range of particles considered.

Table 3.5 Mean Initial Filter Coefficient (m^{-1}), 0.3 m/h

Fabric Lab.	λ_o for particle diameter (μ m)					
No.	2.26	2.85	3.59	4.52	5.70	7.18
25	111	138	171	221	262	-
26	103	126	153	191	210.5	-
27	171	197	227	267	286	333
28	186	213	248	297	315	332
32	21	26	33	43	55	72
44	906	995	1169	1322	1464	-
55	457	490	564	650	754	849
sand	106	122	140	160	181	214

- Means λ_o variations significant.

Table 3.6 Mean Initial Filter Coefficient (m^{-1}), 1.0 m/h.

Fabric Lab.	λ_o for particle diameter (μ m)					
No.	2.26	2.85	3.59	4.52	5.70	7.18
11	212	249	286	332	381	429
25	81	98	116	137	161	179
26	69	84	98	113	129	154
27	164	183	207	238	262	302
28	102	128	156	179	213	-
32	6.5	9.0	12.5	17.0	22.5	-
44	517	540	577	619	645	676
55	349	391	454	530	614	-
sand	64	74	78	84	90	95

- Means λ_o variations significant .

Figures 3.25 through 3.32 show the Initial filter coefficient for the filter media investigated at 0.3 m/h, while Figures 3.33 through 3.40 show the same for an approach velocity of 1.0 m/h . Both sets of results show that for the range of NWF considered, in conformity with literature (120), λ_0 increases with increasing particle diameter, d_p.

3.5.5 Discussion of Results

Figs. 3.41 and 3.42 show the relationship between specific surface (S_o) and λ_o of a number of fabrics (at 0.3 and 1.0 m/h , respectively), covering the representative range of NWF surveyed, clearly, for the three particle diameters considered, λ_o increases with increasing specific surface

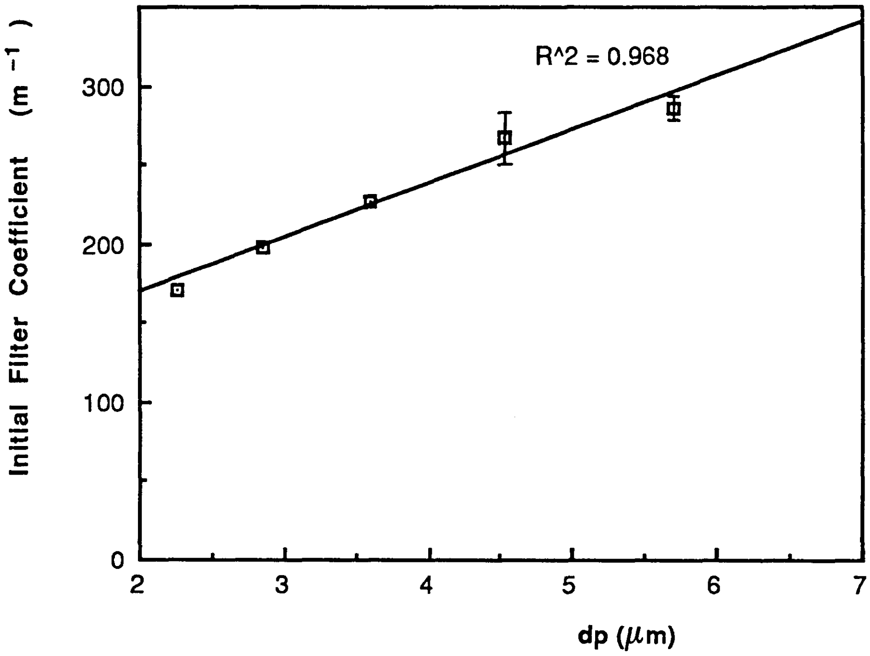


Fig. 3. 25 Initial Filter Coefficient , Lab. No. 27, Coulter analysis, 0.3 m/h ·

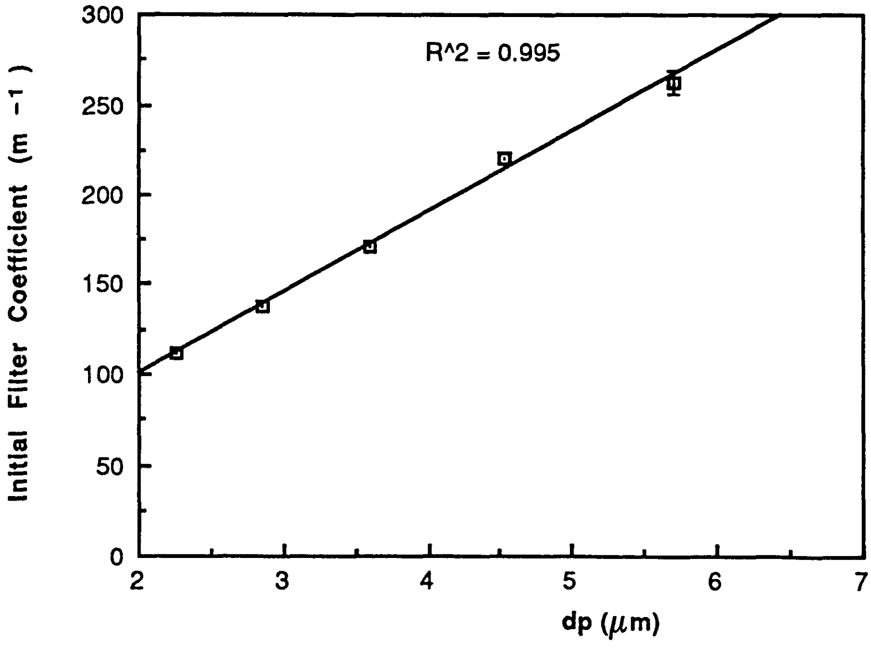


Fig. 3.26 Initial Filter Coefficient, Lab. No. 25, Coulter analysis, 0.3 m/h .

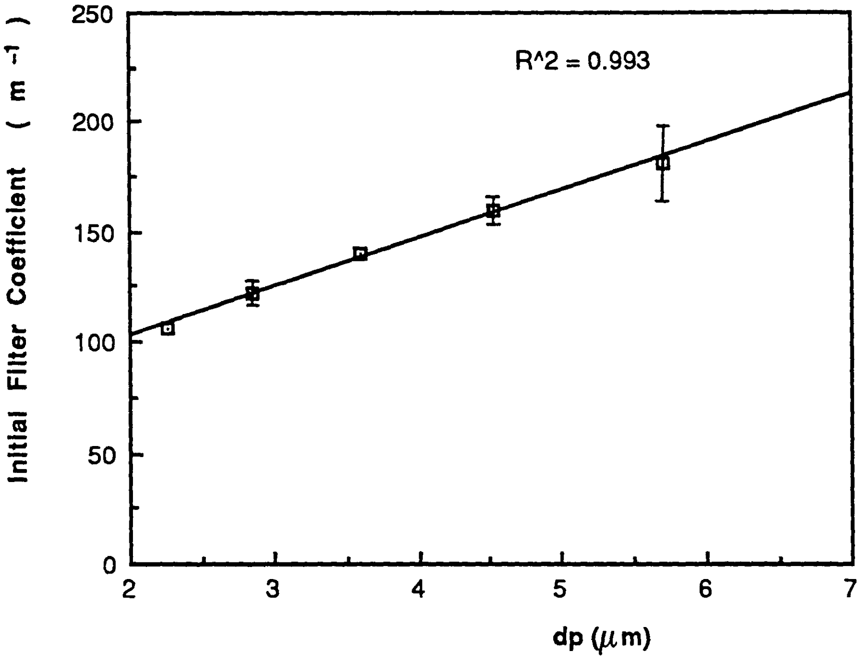


Fig. 3. 27 Initial Filter Coefficient, SSF sand, Coulter analysis, 0.30 m/h .

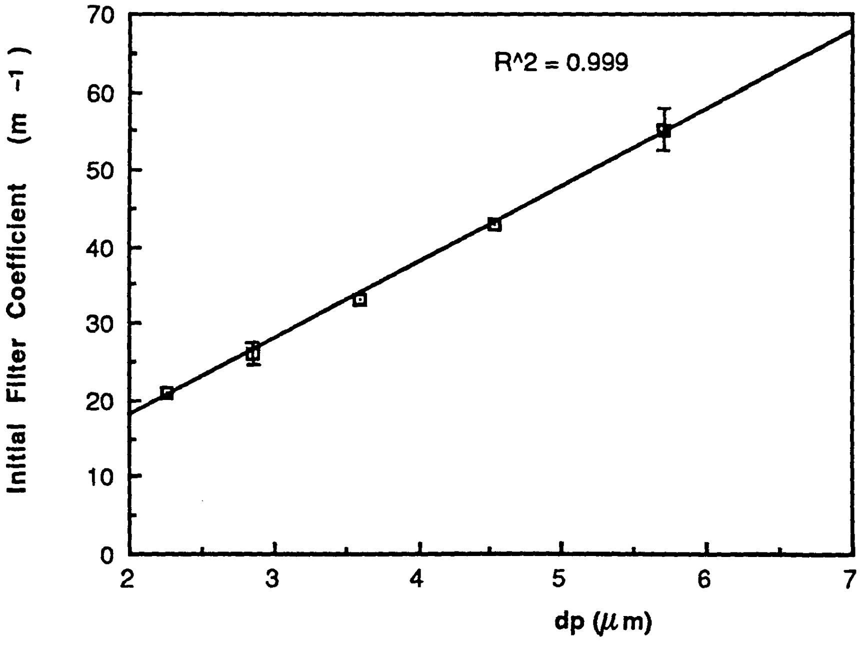


Fig. 3. 28 Initial Filter Coefficient, Lab. No. 32, Coulter analysis, 0.3 m/h .

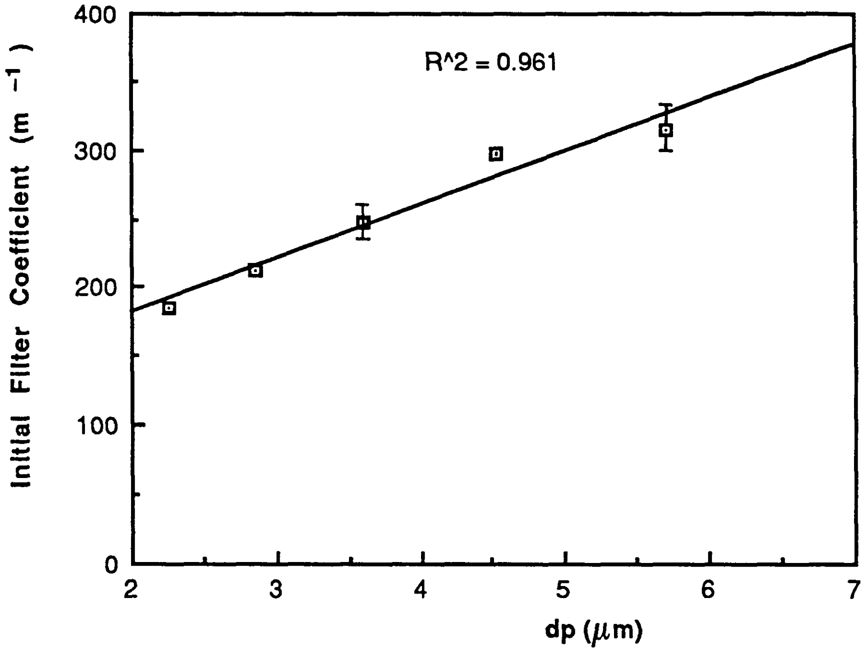


Fig. 3. 29 Initial Filter Coefficient, Lab. No. 28, Coulter analysis, 0.3 m/h .

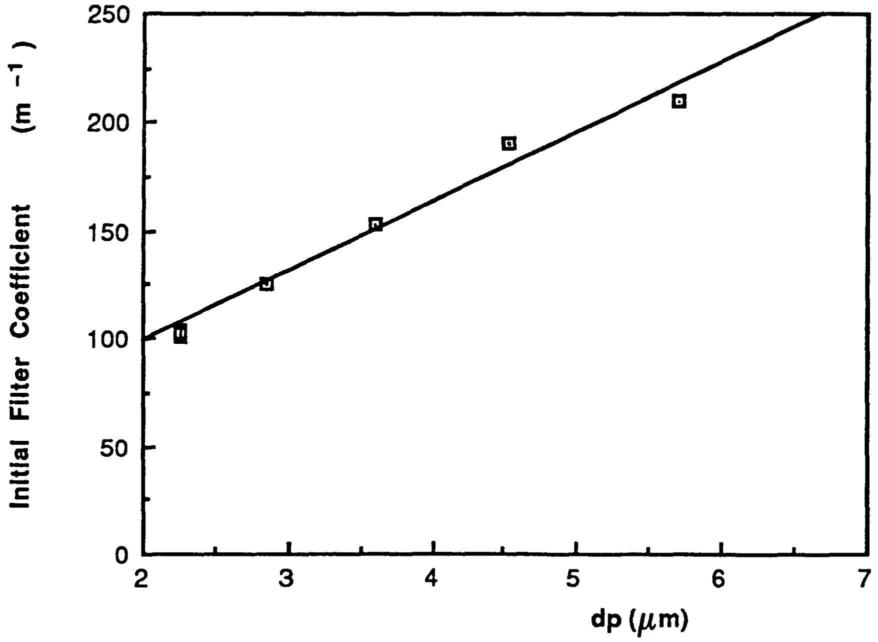


Fig. 3. 30 Initial Filtration Coefficient , Lab. No. 26, Coulter analysis, 0.3 m/h ·

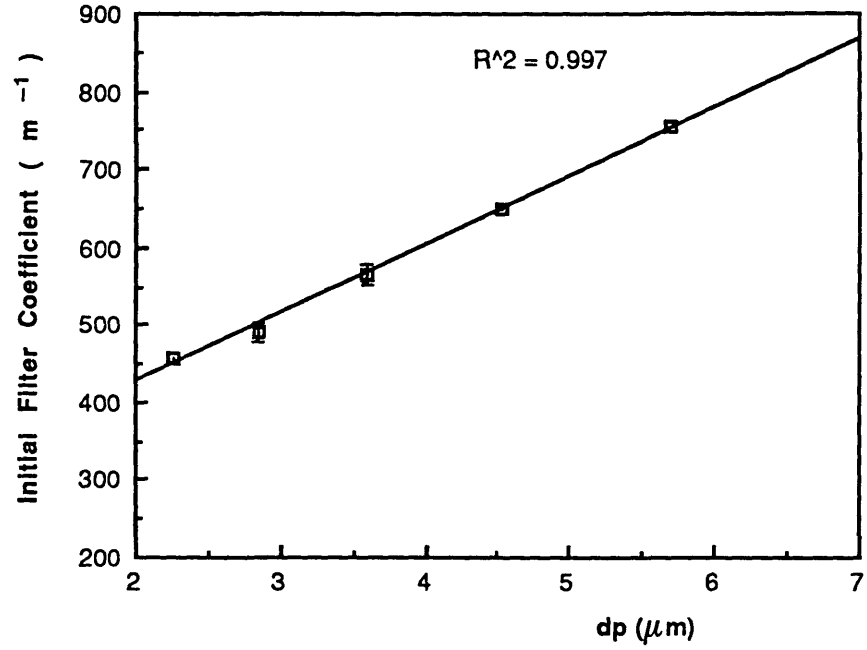


Fig. 3. 31 Initial Filter Coefficient, Lab. No. 55, Coulter analysis, 0.3 m/h .

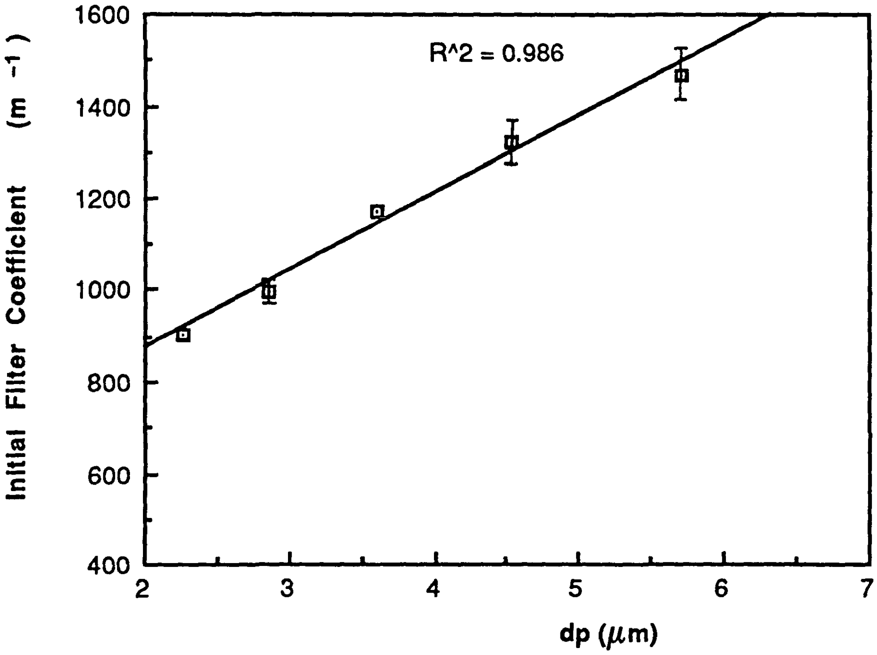


Fig. 3. 32 Initial Filter Coefficient, Lab. No. 44, Coulter analysis, 0.3 m/h .

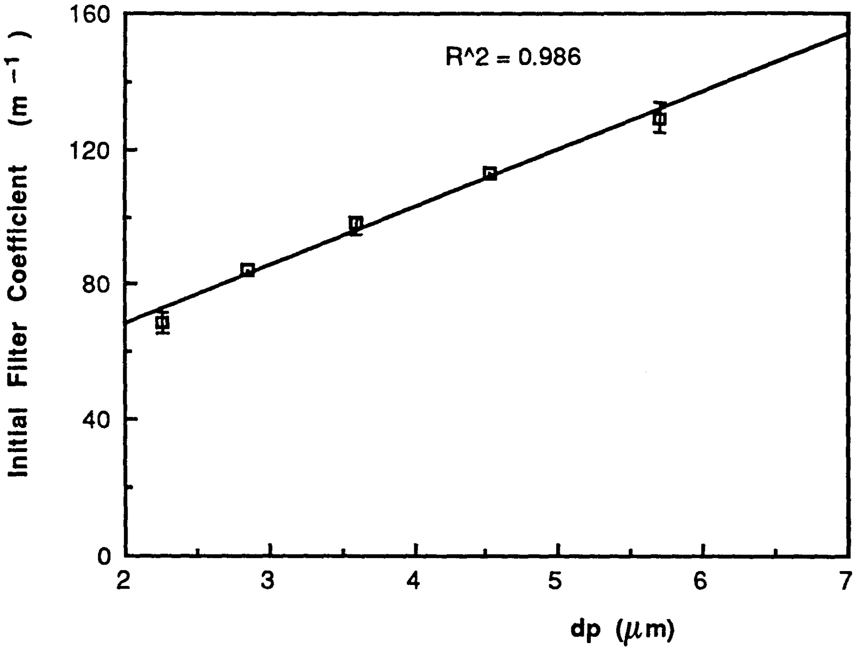


Fig. 3. 33 Initial Filtration Coefficient, Lab. No. 26, Coulter analysis, 1.0 m/h .

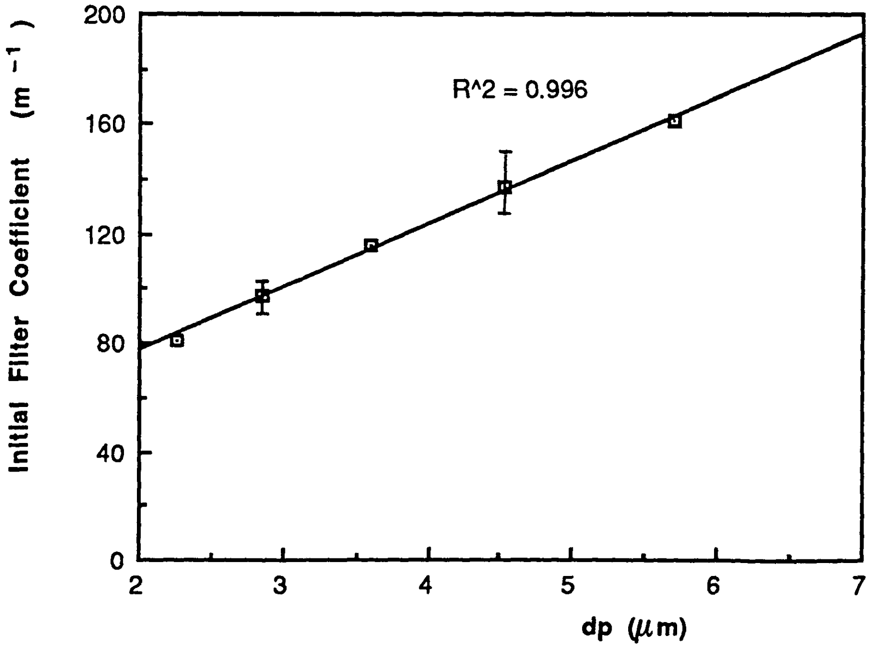


Fig. 3. 34 Initial Filter Coefficient, Lab. No. 25, Coulter analysis, 1.0 m/h .

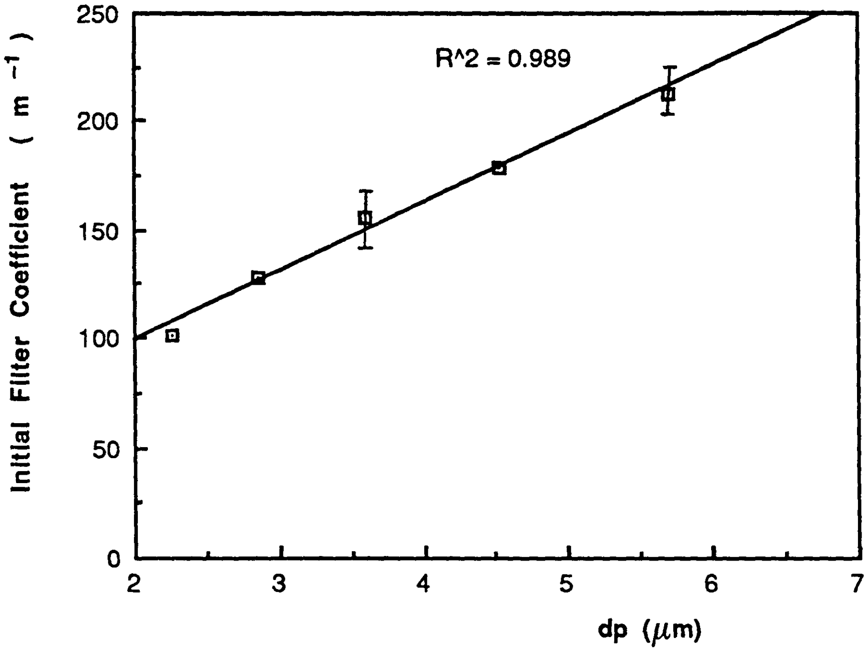


Fig. 3. 35 Initial Filter Coefficient, Lab. No. 28, Coulter analysis, 1.0 m/h .

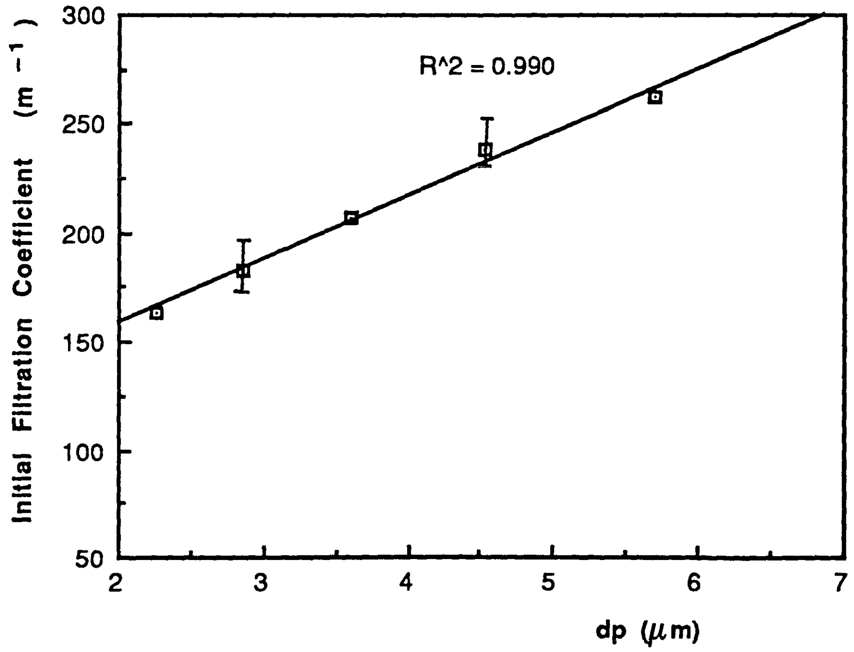


Fig. 3. 36 Initial Filtration Coefficient, Lab. No. 27, Coulter analysis, 1.0 m/h .

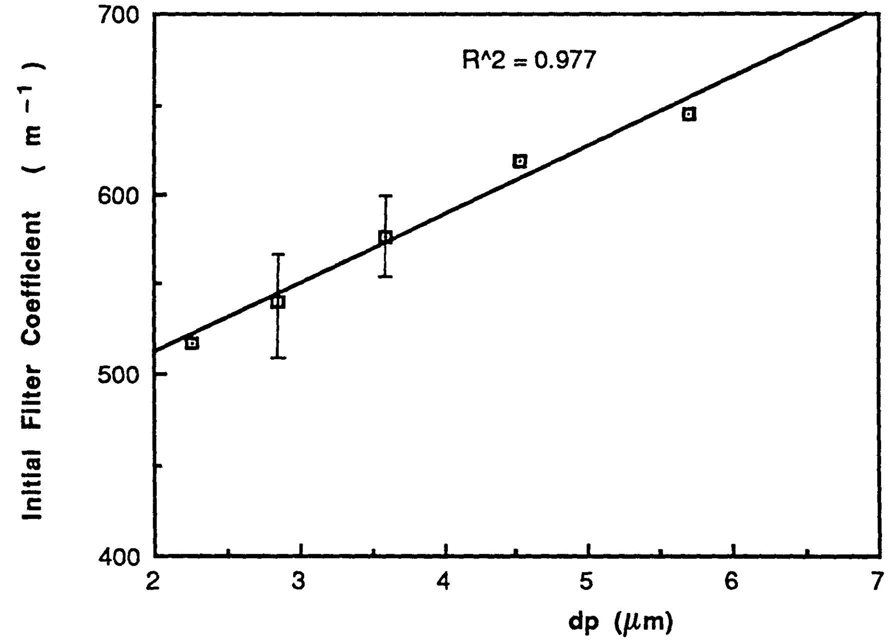


Fig. 3.37 Initial Filter Coefficient, Lab. No. 44, Coulter analysis, 1.0 m/h.

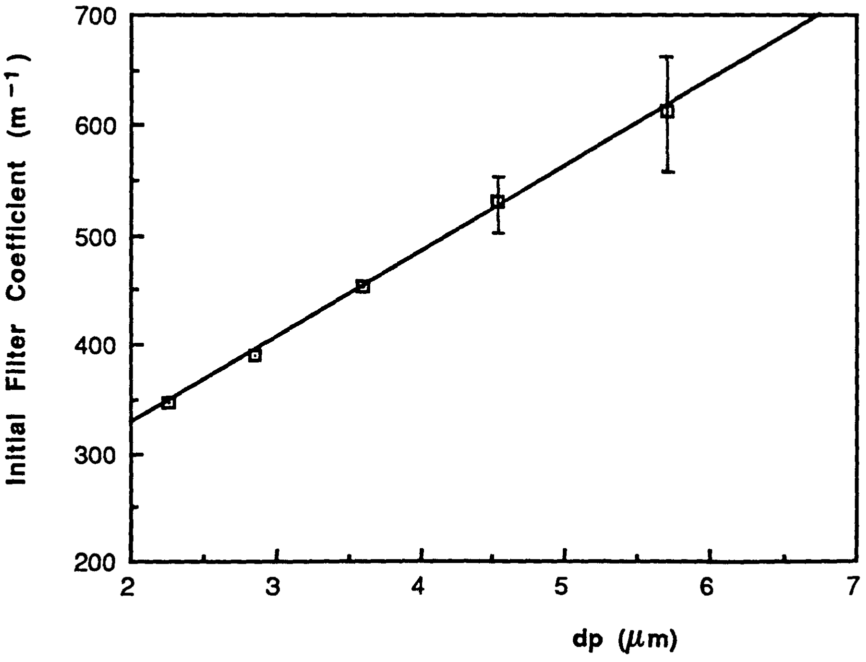


Fig. 3.38 Initial Filter Coefficient, Lab. No. 55, Coulter analysis, 1.0 m/h.

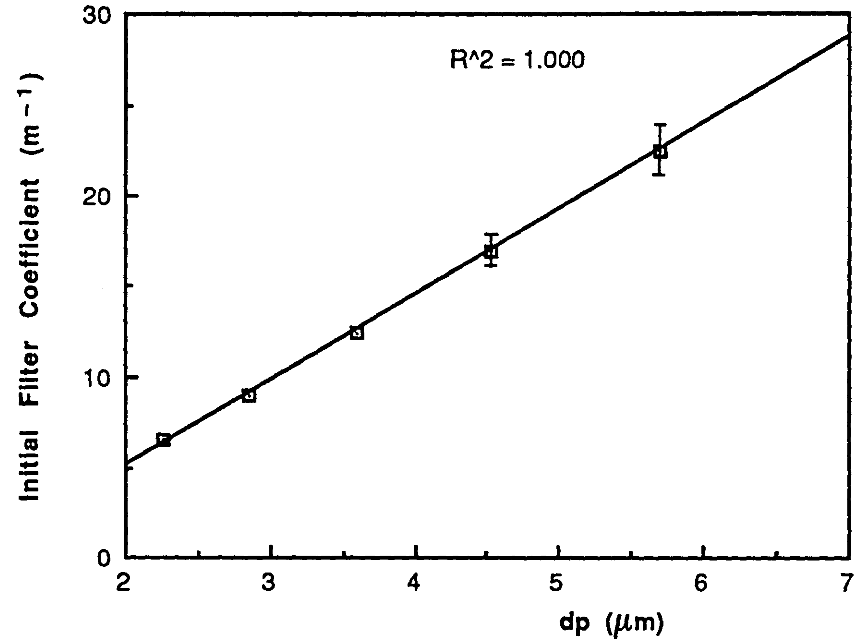


Fig. 3.39 Initial Filter Coefficient, Lab. No. 32, Coulter analysis, 1.0 m/h.

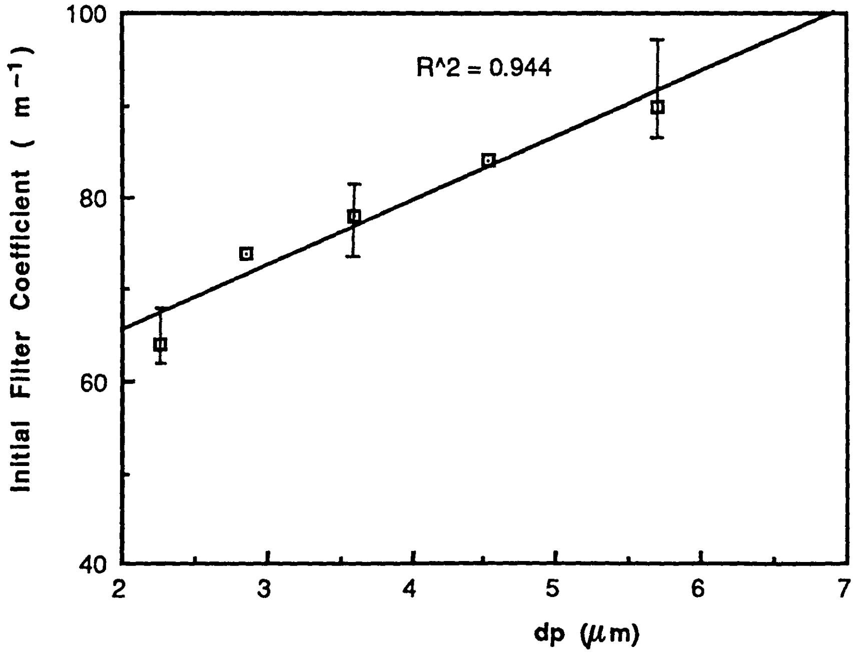


Fig. 3.40 Initial Filter Coefficient, SSF Sand, Coulter analysis, 1.0 m/h.

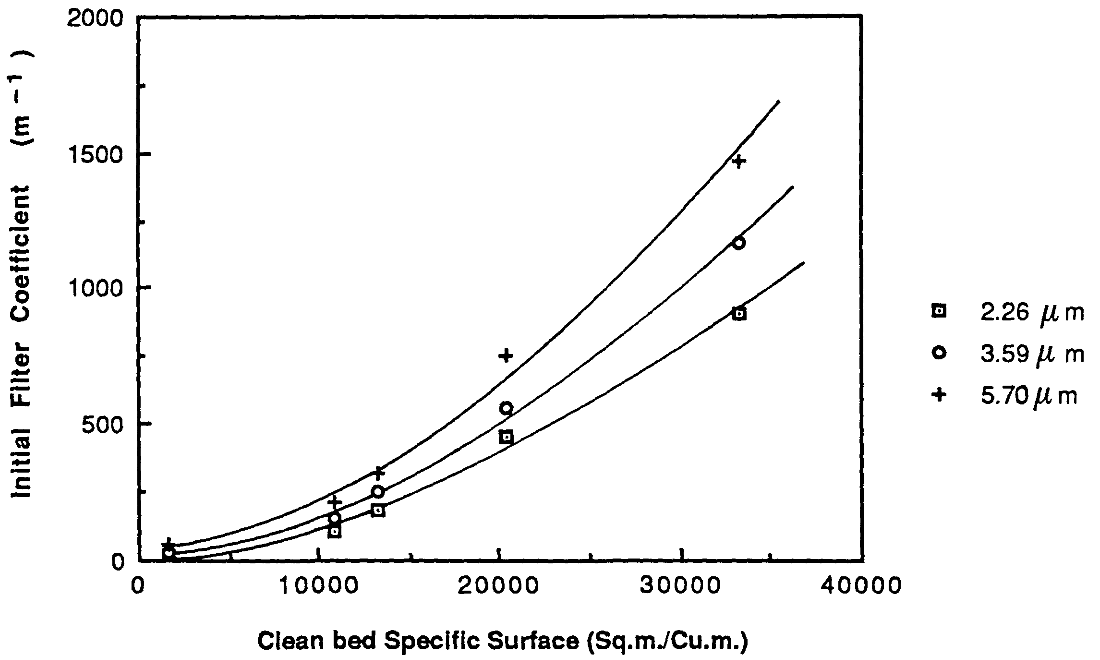


Fig. 3. 41 λ_0- S_0 Relationship, 0.3 m/h .

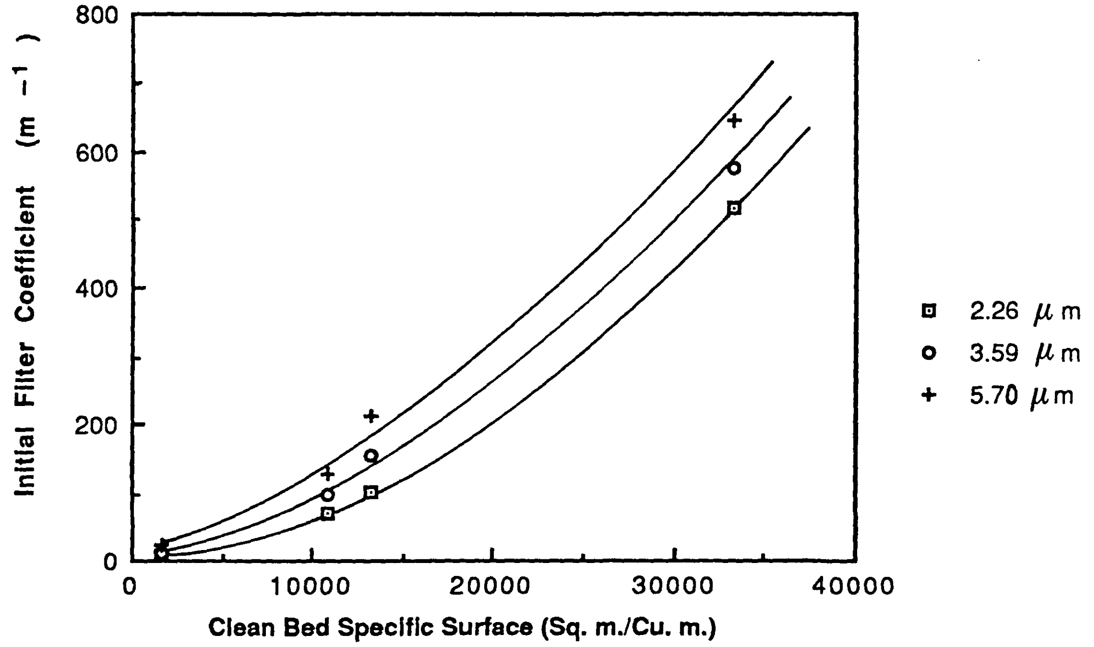


Fig. 3. 42 λ_0 - S_0 Relationship, 1.0 m/h .

and diameter of particles in suspension. Fabric lab. No. 32 which has the smallest specific surface has also got the lowest λ_o while lab. No. 44 with the highest specific surface in table 3.4 has the highest initial filter coefficients at both approach velocities. In line with theoretical predictions in the previous chapter, the experimental results suggest existence of a strong dependency of fabrics initial filter coefficient on clean bed specific surface.

Figs. 3.43 and 3.44 compare the initial filter coefficients of four fabrics and SSF sand at 0.3 and 1.0 m/h, respectively . The λ_o - values of the four fabrics are in accordance to their specific surface areas such that they appear in the following decreasing order ; No. 44, 55, 28 and 32 . As expected, since the estimated specific surface area of sand (see table 3.4) is much higher than Lab. No. 32, its initial filter coefficients are higher than the latter. The slightly higher specific surface of lab No. 28 might account for its higher initial filter coefficient than sand although it must also be remembered that while sand grains are modelled as spherical collectors, fibrous media are represented by cylindrical collector models. These together with differences in the chemical characteristics are expected to show some differences in overall particle capture efficiency as described by Spielman (9) . A comparison of the two figures again

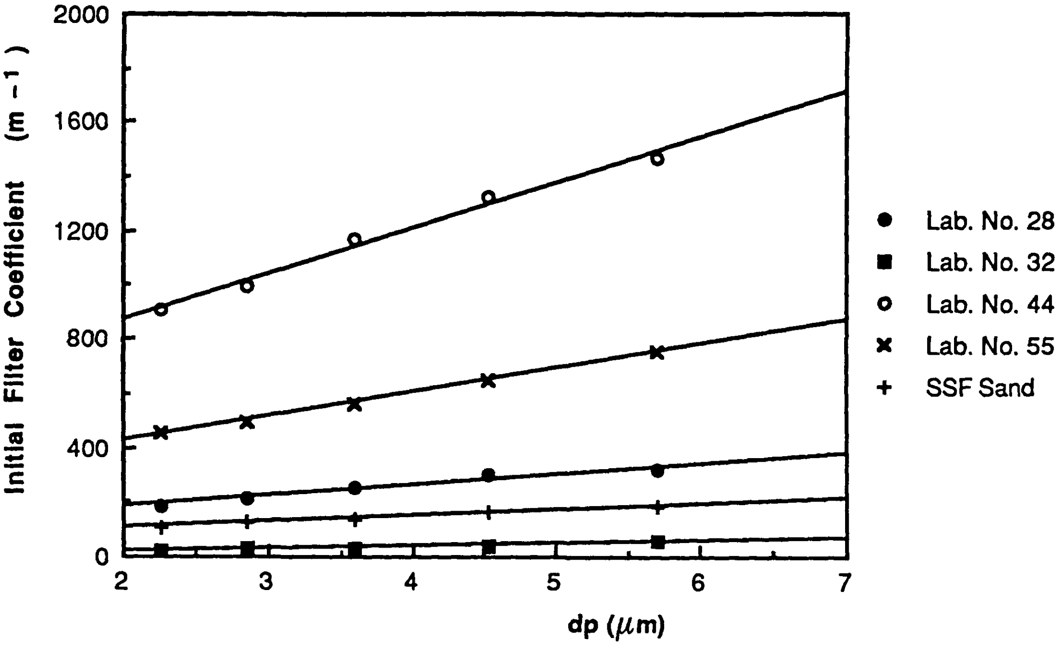


Fig. 3. 43 λ_0 - d_p Relationship, 0.3 m/h .

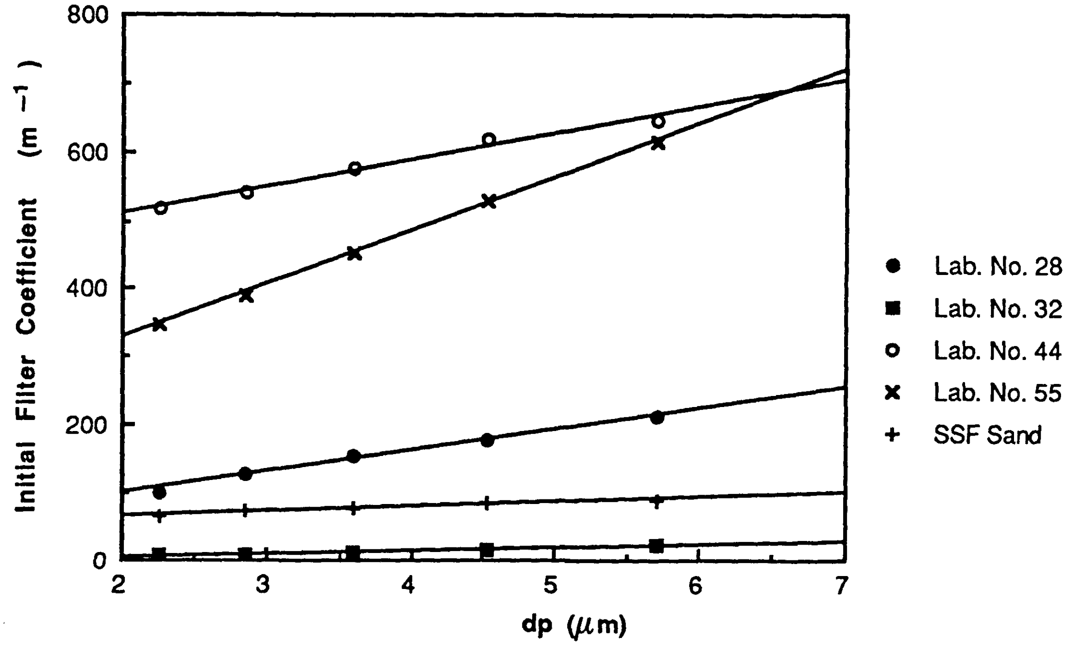


Fig. 3. 44 λ_0-d_p Relationship, 1.0 m/h .

indicates higher initial filter coefficients at the lower filtration velocity of 0.3 m/h .

Figs. 3.45 and 3.46 show the initial filter coefficients of all the fabrics and SSF sand investigated during the experiments. In both cases, the only fabric which has lower initial filter coefficient than sand is No. 32 which also has the lowest specific surface area. The fact that this fabric is bonded by resin spraying and also that its made of a mixture of three relatively coarse fibres can account for the poor initial filtration ability.

From table 3.6 presented on page 135, a comparison of fabric lab. No. 11, 25 and 26 which have very small differences in specific surface area (less than 250 m^2/m^3) shows that the initial filter coefficients of No. 11 are much higher than the other two. In addition, at both approach velocities, the initial filter coefficients of fabric lab. No.25 are higher than 26.

The higher initial particle capture ability of lab. No. 11 might be due to higher efficiency of the smaller diameter of its fibres in comparison to the others. Another factor which might explain the difference in performance might be the fact that lab. No. 11 is made of Polyester fibres which are bound to have different surface characteristics from Polypropylene of which Nos. 25 and 26 are made. It is possible that the Polyester fibres had a more favourable

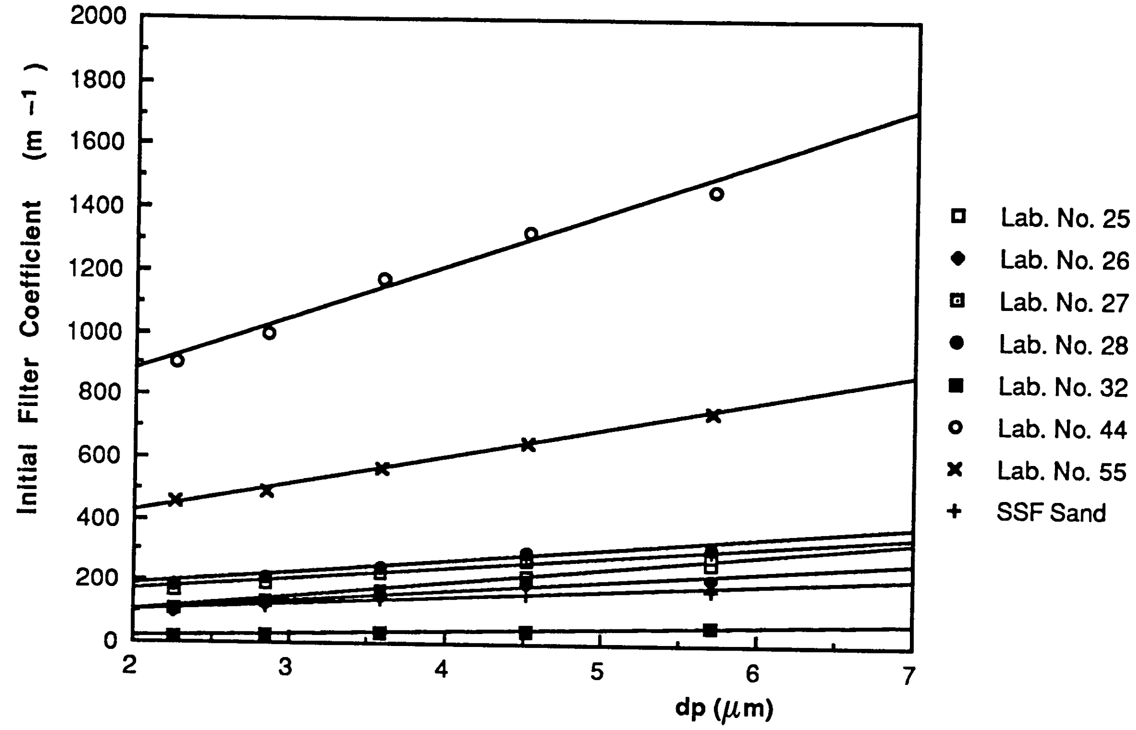


Fig. 3. 45 λ_0 - d_p Relationship, 0.3 m/h .

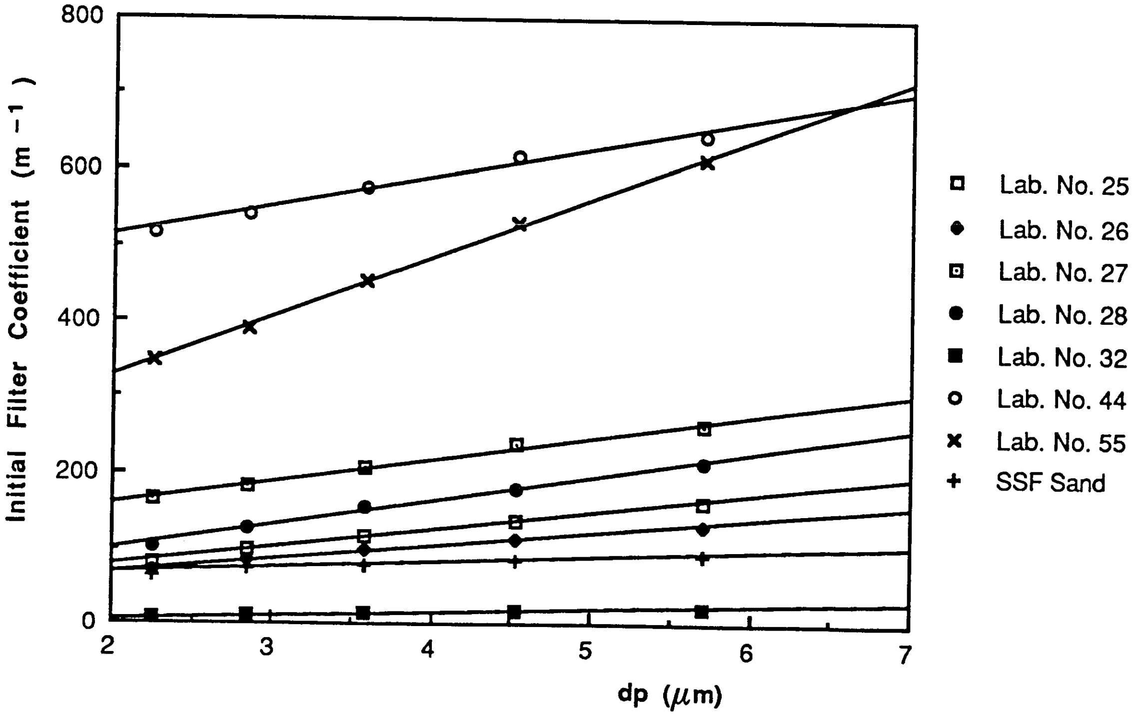


Fig. 3. 46 λ_0-d_p Relationship, 1.0 m/h .

surface charge conditions for particle deposition. In addition to this, while fabric No. 11 is manufactured as a needle-felted spunbonded fabric, lab. Nos. 25 and 26 are produced by needle-felting on carrier threads only. Such differences are likely to account for their performance in terms of overall particle capture ability. As regards fabrics Nos. 25 and 26, the likely cause of better performance of the earlier is its smaller fibre diameter as opposed to the coarser mixture of two fibre diameters of fabric No. 26.

Although the specific surface area of fabric No. 27 is bigger than No.28 by about 1100 m^2/m^3, at 0.3 m/h, the latter has higher initial filter coefficients than the former. However, at 1.0 m/h the filter coefficients of fabric No. 27 are higher than No. 28. Since both fabrics were produced by the same manufacturer from 33 μm diameter Polypropylene fibres, the differences in performance can be a result of variations of fibre or fabric physical properties during manufacturing. However it is not easy to explain the performance differences unless the higher velocity leads to some form of disturbance of particle capture in No. 28 due to the use of multi-filament yarn scrims. As regards lab. No. 55, although it is manufactured purely by thermic bonding of the mixture of Polypropylene and Polyethylene fibres, its relative behaviour is well in accordance to its physical properties. When considering the similarity of porosity of fabrics lab. Nos. 25, 27 and 28, one notes that this parameter does not in any way guarantee similarity in filterability.

The general trend of results is such that in the absence of biological processes, dense fabrics have much higher initial filter coefficients than very porous fabrics. In most cases, the clean bed filtration performance of fabrics are related to the specific surfaces. With the exception of lab. No. 32, most NWF have proved to be better filter media than sand in the absence of biological processes.

Chapter Four

4.0 FIELD ASSESSMENT OF HYDRAULIC AND FILTRATION PERFORMANCE OF A REPRESENTATIVE RANGE OF NWF.

In the preceding chapter, some hydraulic characteristics and clean media filtration performance of a representative range of commercially available NWF were qualitatively and quantitatively established in the laboratory. The results of the laboratory studies were used as a guideline for preliminary selection of NWF for field tests. In this chapter, the performance of a selected, representative, range of NWF in presence of biological processes was evaluated under adverse operating conditions. This involved filtration of a long-term stored, heavily algal laden water (during summer/autumn) at a filtration rate of 0.3 m/h. Such a filtration rate is regarded to be relatively high in conventional operation of SSF. In addition to this, the ability of the fabrics to protect the sand underneath was also assessed. These experiments were carried out on a pilot plant located in the premises of Ashford Common water treatment works, Surrey (see Fig. 4.1).

4.1 Pilot Plant Description

4.1.1 Reservoir Water Sources

The main water works receives raw water from a number of reservoirs after a long period of storage (typically 40 to 60 days). The treatment scheme consists of microstraining, slow sand filtration and disinfection. Between May 1985

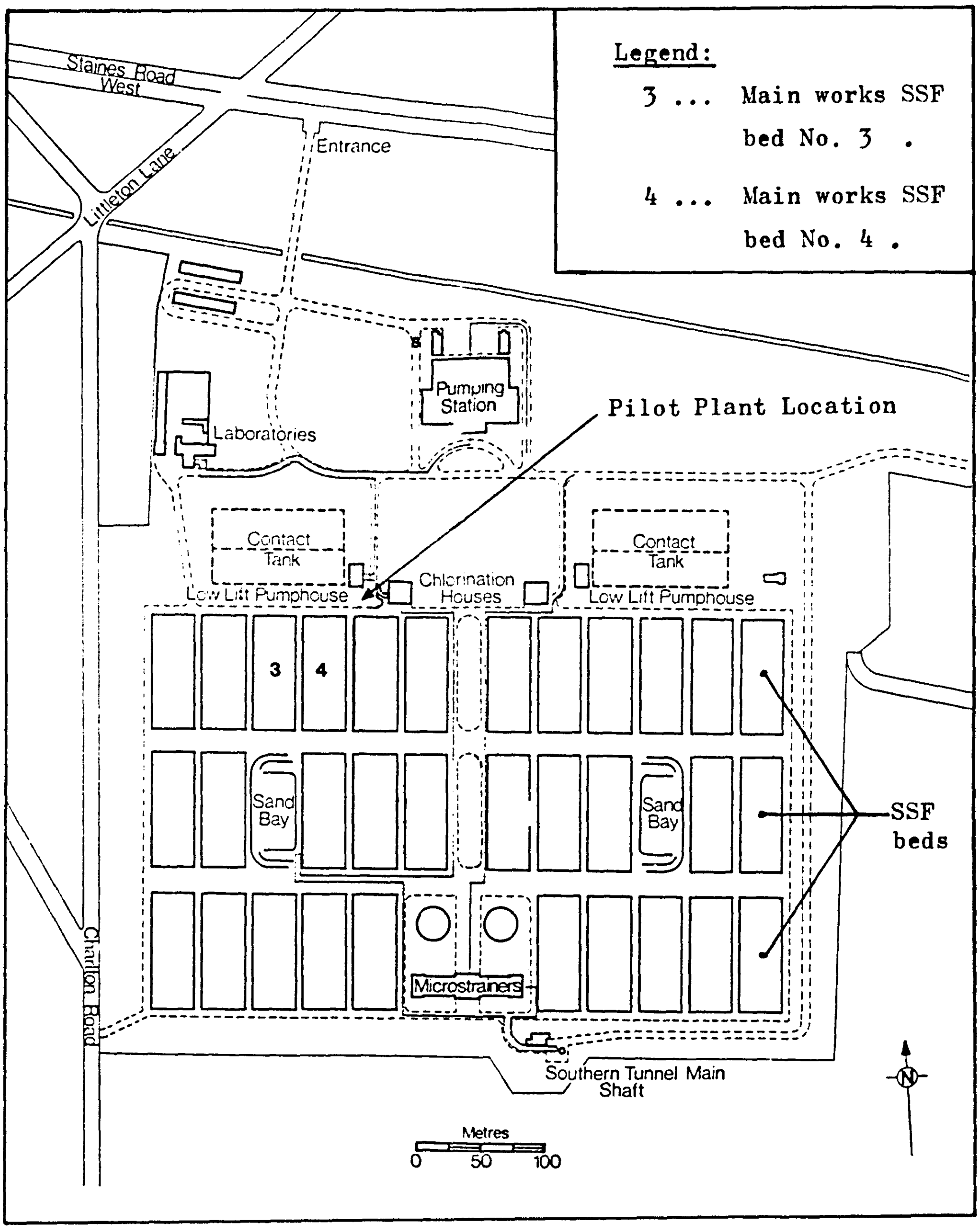


Fig. 4.1 The Location Plan of Ashford Common Pilot Plant.

and May 1988, the main sources of raw water were the Queen Mary and Wraysbury reservoirs. Occasionally either the King George VI or Datchet reservoir was combined with the Queen Mary or Wraysbury reservoir to supply the main works at Ashford Common with raw water. The combinations depended on the water quality at the time. During the period of study described in this chapter which extended from mid-July to the end of October 1986, the main works raw water was supplied from the Queen Mary in combination with either Wraysbury or Datchet reservoir.

4.1.2 Pilot Plant Layout

After the initial assembly of the pilot plant and use for a short period by Bridges (63) in 1985, between May and mid-July 1986, the pilot plant was modified to appear as indicated on Fig. 4.2 . The pilot plant inlet water was extracted from the supernatant (influent) water of either the SSF bed No. 3 or 4 (indicated on Fig. 4.1) with two NOVA 300 DAB automatic submersible pumps (Hodson, Croydon Ltd, UK). The water was pumped into a header tank located on top of the valve house (see plate.18). The tank was connected to a 50 mm diameter outlet pipe which fed water to all the six SSF units denoted as AFM1 through AFM6 as shown on Fig. 4.2. This main supply pipe was provided with an air release valve at the dead end. A fabric wash water pipe was also tapped on the main supply pipe.

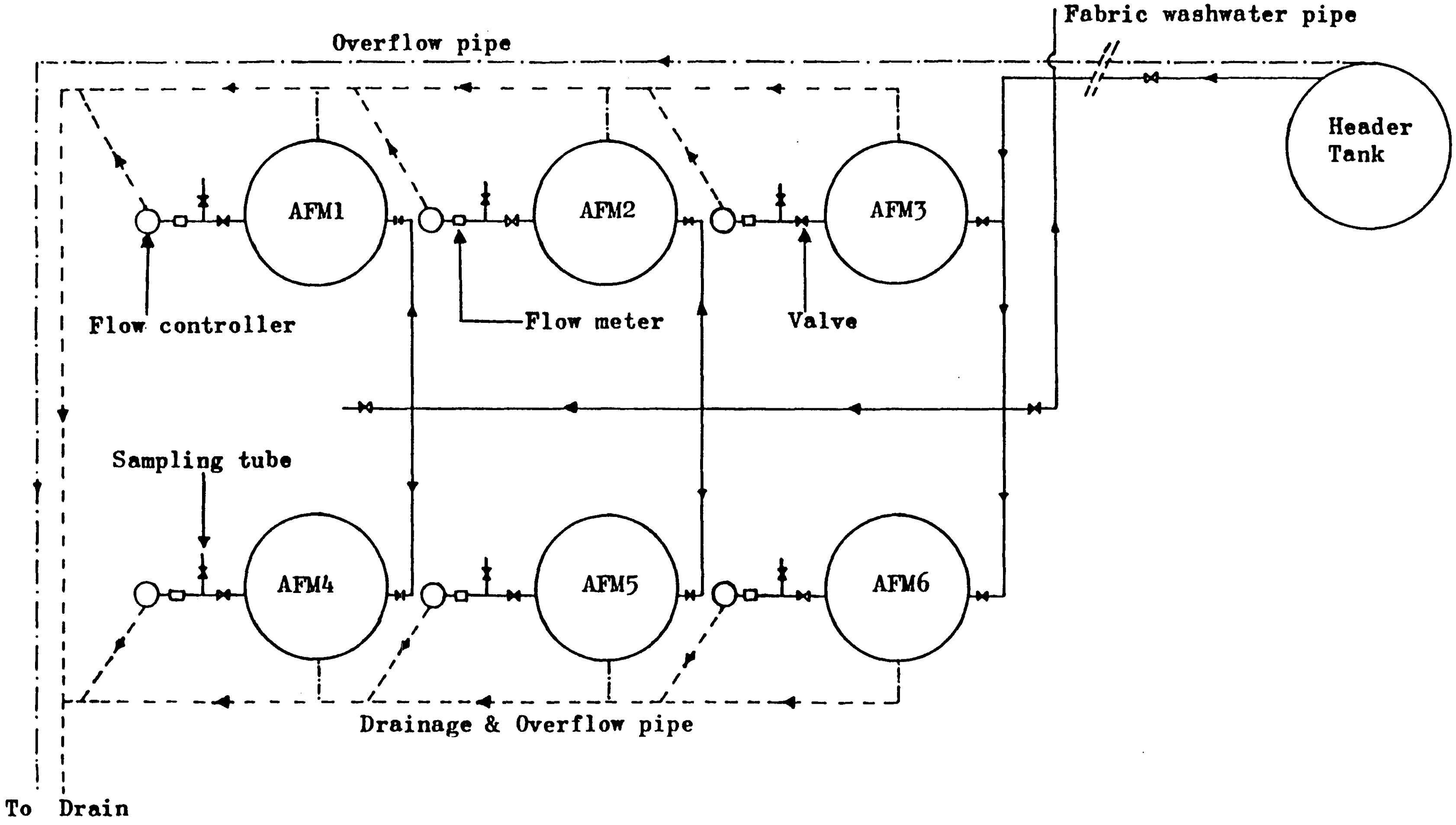


Fig. 4.2 Layout Plan of Ashford Common Pilot Plant.

Plate.18 Layout of the Ashford Common Pilot Plant .

Fig. 4.3 shows a typical cross section through a SSF unit in the pilot plant. The SSF units were circular (U.V.-stabilized) medium density Polythene tanks with a top diameter of 1.4 m and a depth of 1.2 m . At mid-height the tanks were manufactured with a 5 cm wide rim meant to allow stacking-up of units during transport. Use was made of this rim to allow the fabric an overlap on the edges. The under-drainage system consisted of 40 mm diameter perforated pipes placed in a thickness of about 120 mm gravel. On top of this a 480 mm depth of sand was placed. Inlet water flowed through the sand and gravel layers prior to going through a totalizing Kent flow meter (PSM, 25 mm) and onwards to the effluent flow controller consisting of a float controlled telescopic tube operating as indicated on Figs. 4.4 (a) and (b) at the begining and end of the filter run time, respectively. The header tank was provided with a separate overflow pipe while the overflows from individual SSF units were connected to the filtrate drain pipe system (see Fig. 4.2).

To enable collection of samples of the filtrate, a sampling pipe was provided upstream of the flow meters. Each SSF unit was constructed with eight manometer tubes individually located at heights of 70 mm above the rim (No.1), at the level of the rim (± 0 mm, top of sand bed level (No.2)), 25 mm (No.3), 55 mm (No.4), 80 mm (No.5), 110 mm (No.6) and 210 mm (No.7) below the rim level. The eighth manometer tube was located within the supporting

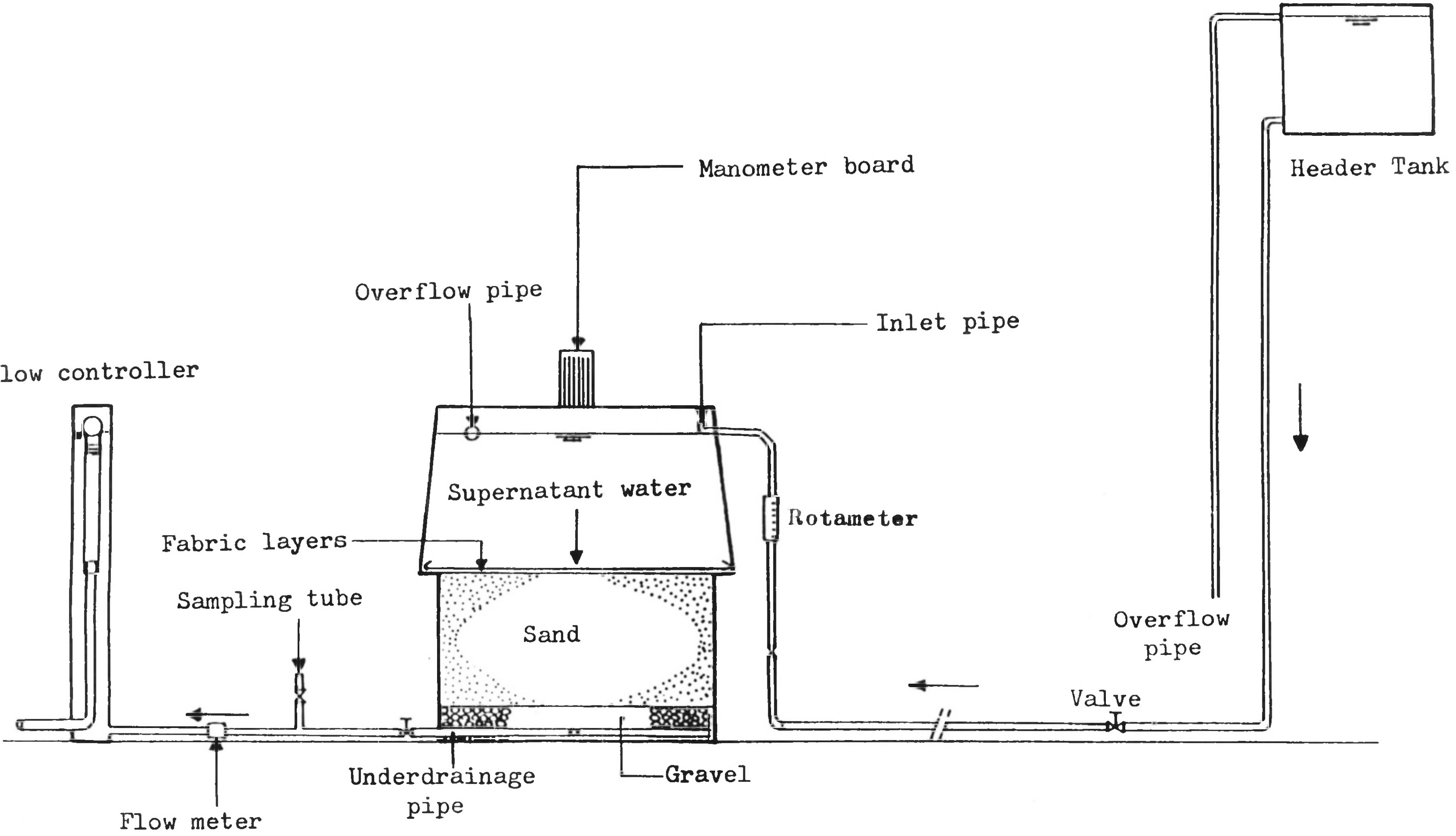
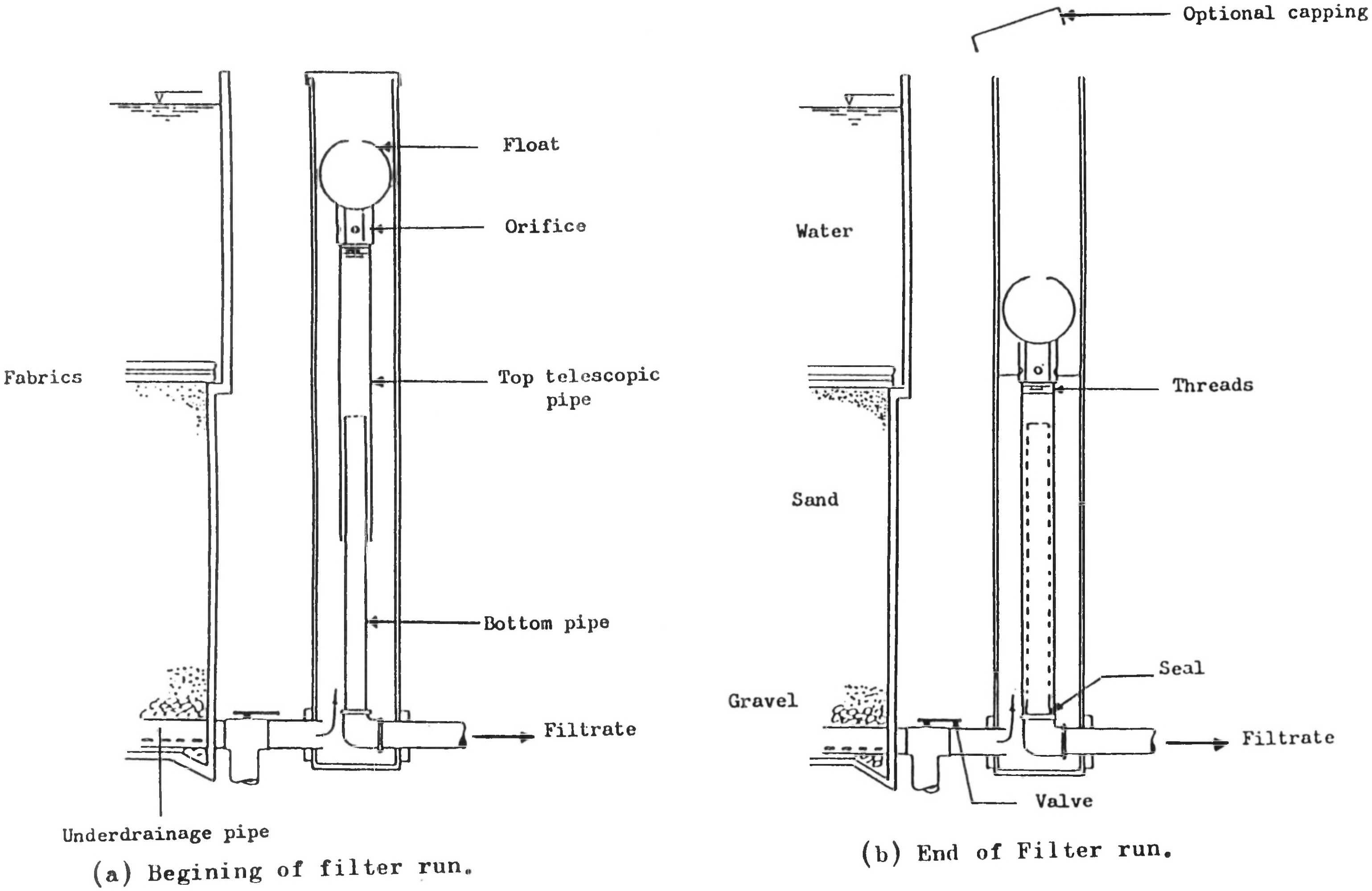


Fig. 4.3 Typical Cross Section Through a SSF Unit.



(a) Begining of filter run.

(b) End of Filter run.

Fig. 4.4 Ashford Common SSF Flow Controler Details (modified, after Lloyd et al, 1986, (50)) gravel layer. Plate.19 is a close-up of the SSF units showing the manometer board, flow controller, inlet and overflow pipes.

4.1.3 **Filter Media**

The characteristics of SSF sand used has already been reported in the previous chapter (section 3.2), Fig. 3.3 gives the mean grading curve of the sand installed in the six SSF units in the pilot plant. As regards the fabrics, table 4.1 gives the list of NWF installed on top of the depth of 480 mm of sand in each SSF with the exception of AFM2 which was the reference and therefore not protected by any fabric.

Table 4.1 NWF Installed in the SSF units.

SSF Unit	Fabric Lab. No.	Number of Layers	Nominal Thickness (mm)	Total Fabric Thickness (mm)
AFM1	44	10	1.3	13
AFM2	None	-	-	-
AFM3	32	2	13	26
AFM4	55	13	1	13
AFM5	32	1	13	13
AFM6	44	5	1.3	6.5

4.2 **Analysis Methods**

The parameters monitored during this research programme included water temperature, turbidity, pH, bacteriological quality, particle size distribution, water Particulate

Plate.19 Close-up of the Slow Sand Filter Units at Ashford Common Pilot Plant .

Organic Carbon (POC) and Chlorophyll-a (Chl-a), SSF sand profile POC, Chl-a and silt content.

4.2.1 Temperature

The water temperature was measured daily at approximately the same time of the day with a mercury thermometer capable of registering temperatures between -10 to +40 °C.

4.2.2 Turbidity

This parameter was measured in Nephelometric Turbidity Units (NTU) with a HACH model 2100A (Camlab, UK) turbidimeter.

4.2.3 pH

pH was measured at Imperial College by a probe connected to an ORION Research, model 701 digital pH-meter.

4.2.4 Bacteriological Quality

Presumptive coliforms and Faecal coliforms enumeration was carried out on the basis of multiple tube tests at the New River Head Thames Authority water quality laboratory, by Thames Water personnel, according to the standard methods described in the Bacteriological Examination of Drinking Water Supplies, 1982, Report No.71, (121). The results were reported in numbers per 100 ml.

4.2.5 Particle Size Distribution

This was done at the Thames Water Wraysbury laboratory on a model TA II /PCA I Coulter Counter with a 200 μm orifice diameter tube. This orifice diameter enabled the analysis of particles of size ranging from 4 to 64 μ m to be done.

4.2.6 Water POC and Chl-a

These non-standard analysis procedures, explained in detail in appendix.2 were derived and have been tested over a long period by Thames Water (63,87,122) . They were done by Thames Water personnel at Wraysbury laboratory. The POC analysis is based upon the oxidation of Carbon using a weak Ferrous Ammonium Sulphate to determine POC as mg C / m^3. The Chl-a is evaluated from absorbance measurements in a spectrophotometer.

4.2.7 SSF Sand Profile POC, Chl-a and Silt Content

A suspension made from a known weight of SSF sand profile sample is filtered in a manner explained in appendix.2. The suspension is then used for sand POC and Chl-a determination and the only major variation is the use of a stronger Ferrous Ammonium Sulphate . In addition, the volume of the standard solution used for titration is doubled. The dry weight of silt is then determined by burning the volatile material in an electric muffle furnance. Changes in the weight of the filter paper are then used to calculate the quantity of silt present in the sand profile sample.

4.3 Raw Water Characteristics

Fig. 4.5 shows the mean monthly water POC for the reservoir(s) water between May 1985 and May 1988 while Fig. 4.6 shows the mean monthly water Chl-a for the same period.

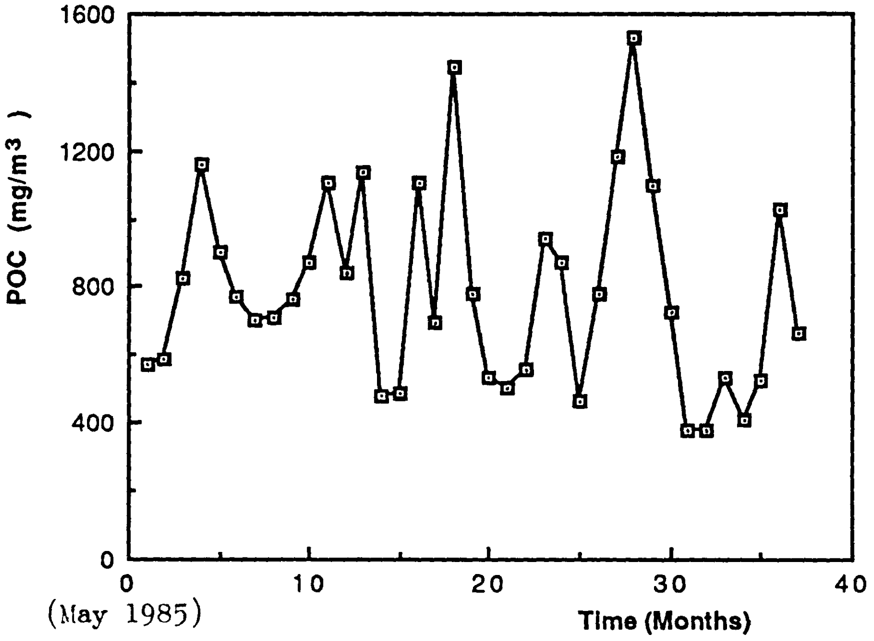


Fig. 4. 5 Mean Monthly Reservoir Water POC .

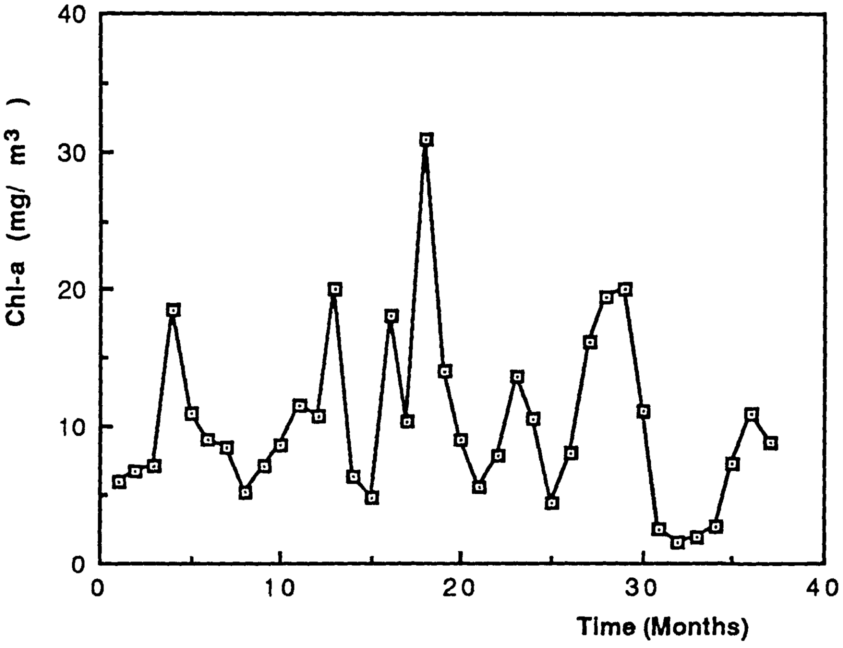


Fig. 4. 6 Mean Monthly Reservoir Water Chl-a .

It must be noted that these results were evaluated on the basis of the weekly analysis done by Thames Water Wraysbury laboratory. During this period, the maximum and minimum reservoir water mean POC was 1529.2 and 376 mg C /m^3, respectively. As regards Chl-a, the same were 30.8 and 1.5 mg/m^3. However, the average data which was sometimes evaluated on the basis of 50%:50% mix by volume (for example Queen Mary:Wraysbury reservoir) tended to mask the individually observed peaks in the reservoirs. Figs. 4.7 and 4.8 show the mean monthly POC and Chl-a of the microstrainer filtrate during the period under mention. The data was evaluated in the manner similar to reservoir water data. In this case, the maximum and minimum microstrainer filtrate monthly POC was 773 and 222.3 mg C/m^3, respectively. For Chl-a, the same were 9.81 and 1.35 mg/m^3, respectively. The considerable fluctuations of POC and Chl-a during the field test programme did not suit characterisation on the basis of average values.

Between May 1985 and May 1986, the main algae identified in the reservoir waters were Diatoms, Greens and Blue Green . Between May and October 1985, some Tribonema and Dinoflagellates were identified and in January 1986 a lot of Stephanodiscus hantzschii were identified. As regards the animal species, between May 1985 and May 1986 Crustaceans (Daphnia sp.), Cyclops sp., Rotifera and Copepods were the most predominant. However, it must be

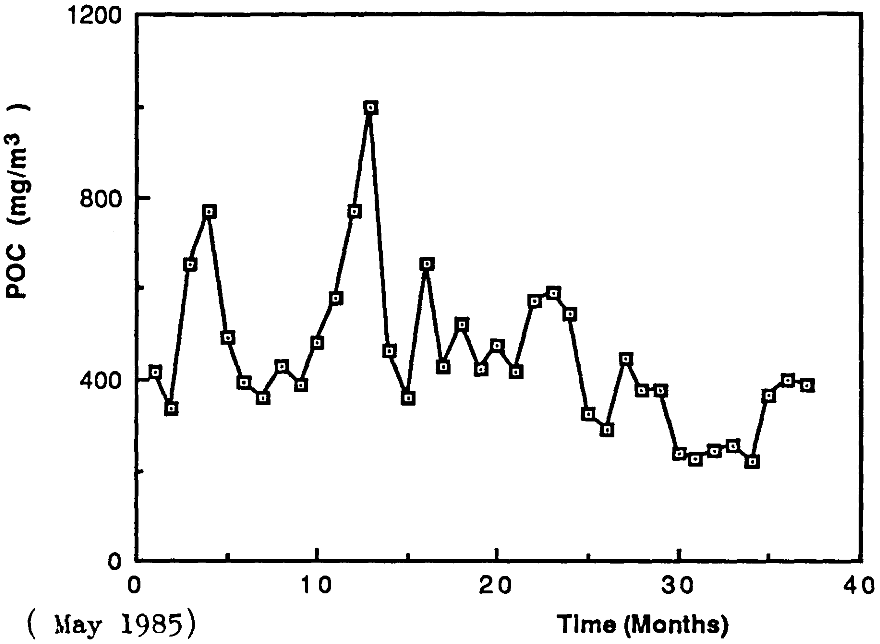


Fig. 4. 7 Mean Monthly Microstrainer Filtrate POC .

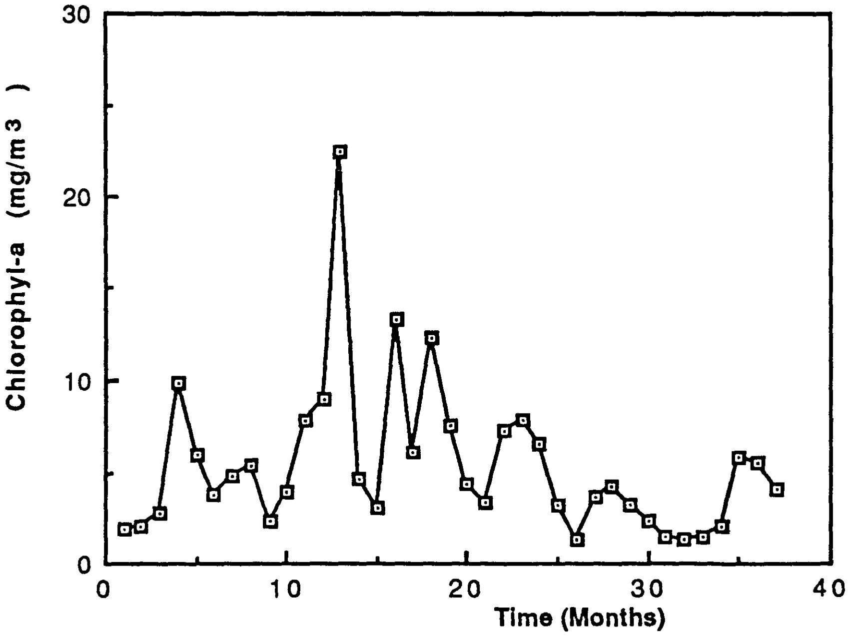


Fig. 4. 8 Mean Monthly Microstrainer Filtrate Chl-a .

realized that although it is worthwhile to have a knowledge of the biochemical quality of reservoir water, experience (23,38,54) has shown that the pattern of algae species in the reservoir water subject to primary filtration (or in this case microstraining) does not necessarily correspond to that in the subsequent SSF basins.

During the actual experimentation period which lasted from mid-July until the end of October 1986, the dominant algae in the reservoir(s) were Diatoms , Blue Green, Greens and Dinoflagellates. At the same time, bed penetration of Aphanizomenon sp. was reported in the main works. The only dominant animal group was the Cladocerans.

4.3.1 Inlet Water Quality

The characteristics of the inlet water to the pilot plant which was extracted from the supernatant of either the main works SSF No. 3 or No. 4 are shown on Fig. 4.9 which gives the POC variation from the 23/07/86 until the 22/10/86. Fig. 4.10 shows the Chl-a variation during the same period. Figs. 4.11 and 4.12 show the variation of inlet water presumptive coliform and faecal coliform counts, respectively. The inlet water pH and turbidity variations are shown on Figs. 4.13 and 4.14, respectively.

4.4 General Conduct of Pilot Plant Tests

The pilot plant was commissioned on the 13/07/86 which was

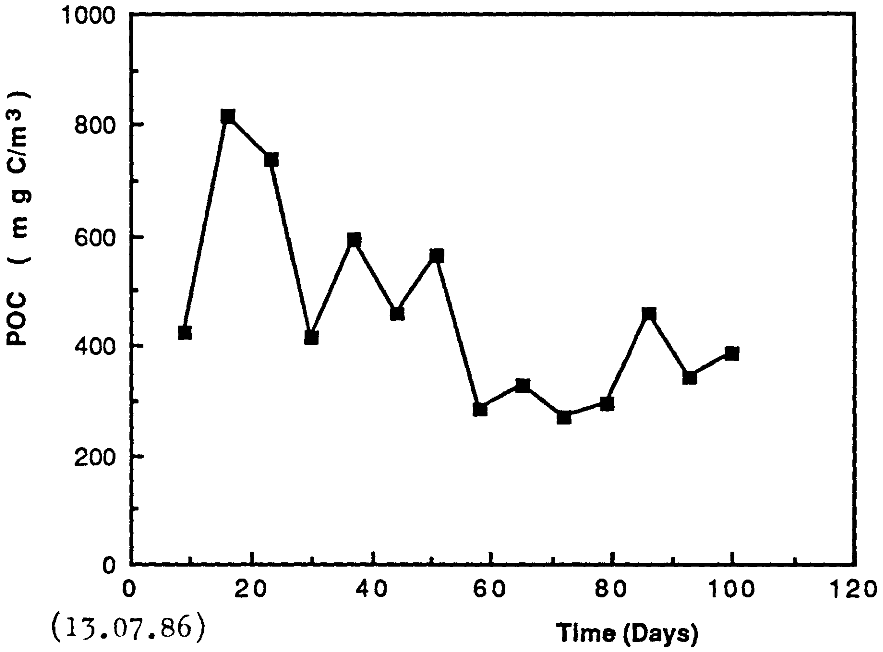


Fig. 4.9 Inlet Water POC .

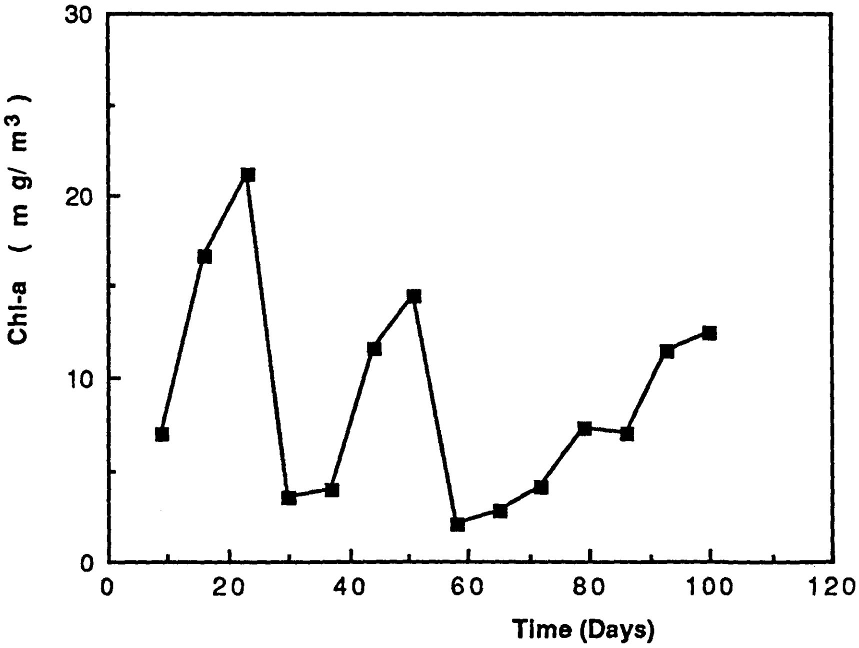


Fig. 4.10 Inlet Water Chlorophyll- a.

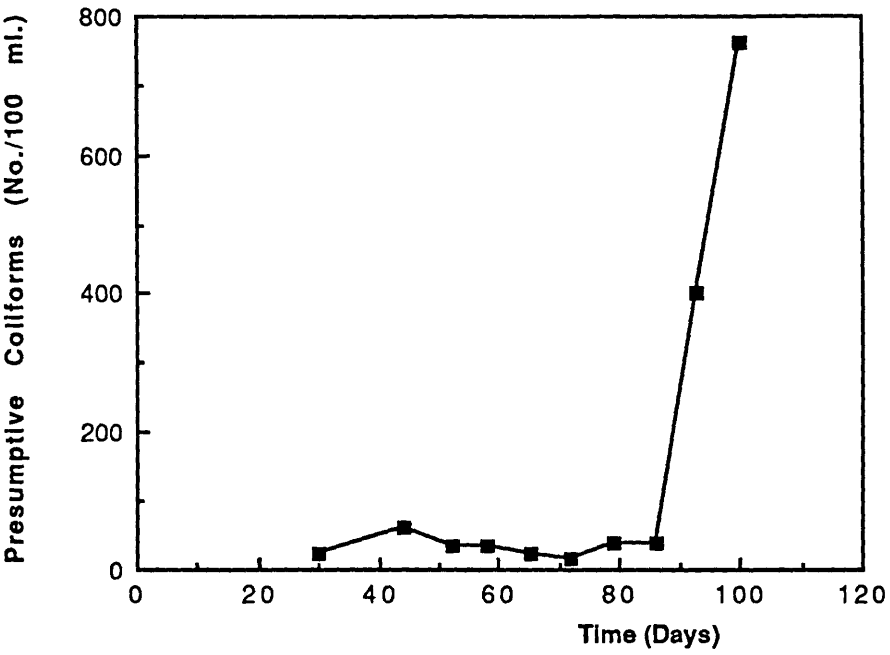


Fig.4.11 Inlet Water Presumptive Coliforms.

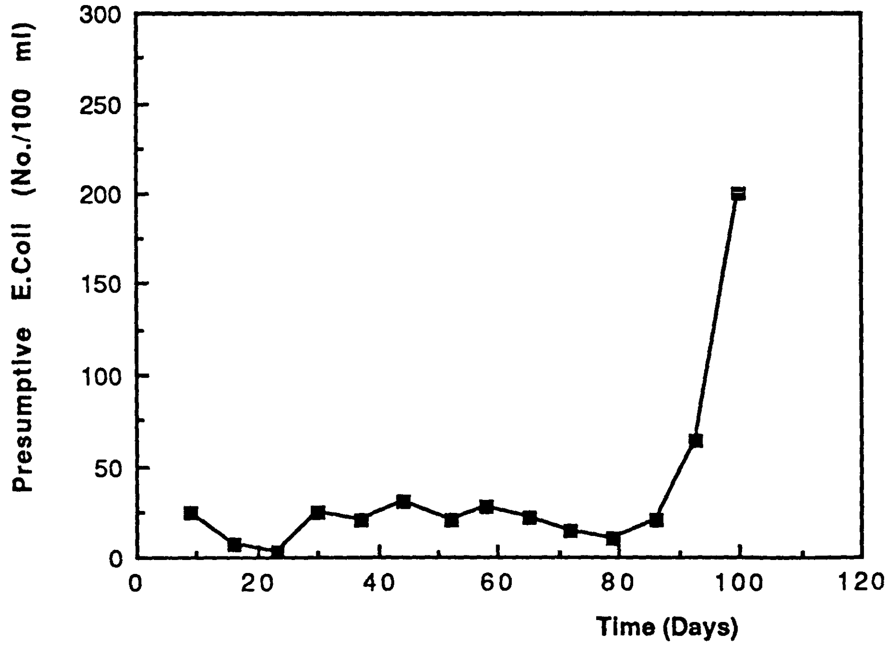


Fig. 4.12 Inlet Water Presumptive E.Coli ·

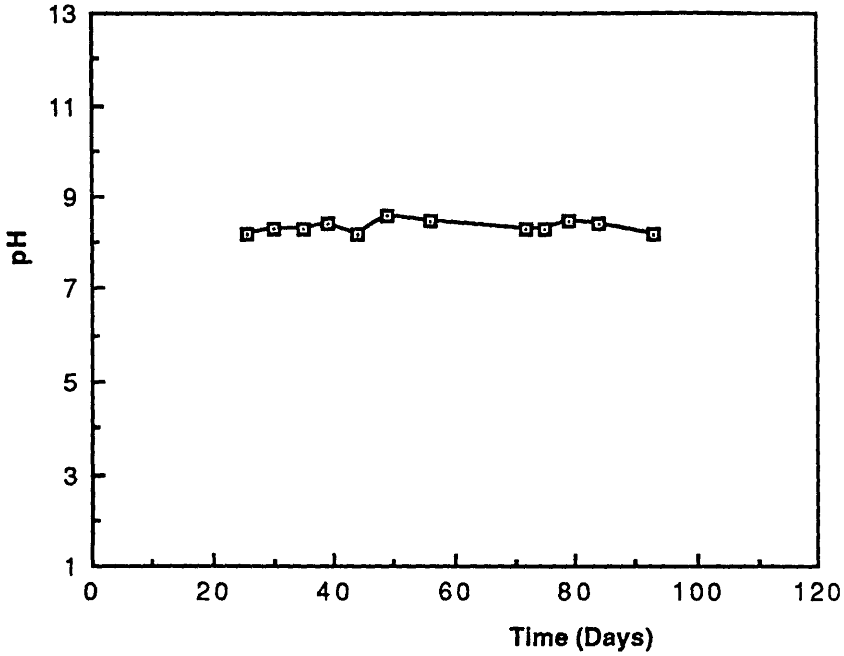


Fig. 4.13 Inlet Water pH .

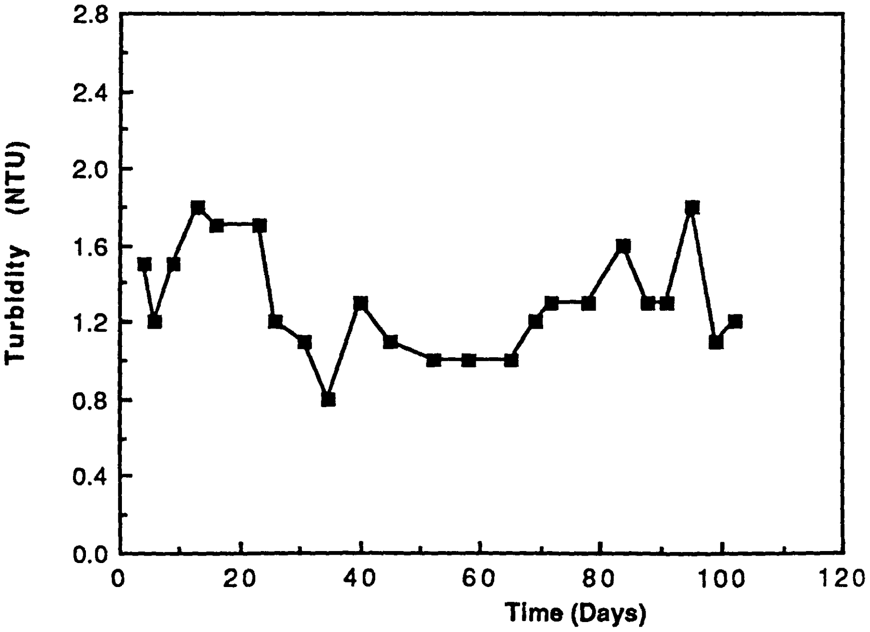


Fig. 4.14 Inlet Water Turbidity ·

the reference day (day number zero) for the field test programme reported in this chapter. The temperature of the pilot plant SSF supernatant water was monitored daily at approximately the same time of the day. The performance of the filters during autumn was of interest due to the strong dependence of bio-chemical processes on water temperature (15). The inlet water pH was taken once per week between 8/08/86 and 15/10/86. Turbidity was analyzed daily for the inlet water and the six SSF filtrates during the research programme. The bacteriological quality analysis for inlet water and SSF filtrates was done once per week. While the presumptive Faecal coliforms were enumerated during the whole research programme, presumptive coliforms were enumerated only from 13/08/86.

Particle size distribution, water POC and Chl-a were analyzed once per week for the inlet water and the SSF filtrates. Before filling the SSF units with water for the first time, three samples of clean sand were taken for POC, Chl-a and silt content analysis. As regards the SSF sand profile POC, Chl-a and silt, the samples were taken at the end of the filter runs only for AFM1,2,4 and 6 . The core SSF sand samples were taken from the top 100 mm with an 125 mm diameter sharp edged plastic cylindrical sampler and then sub-divided into four equal thicknesses of 25 mm each in order to get an idea of the distributions in the sand beds.

Filter head loss was monitored daily with the help of eight manometer tubes provided in each SSF unit. Filtration rate was confirmed daily and/or adjusted when necessary in order to ensure operation at the designated filtration rate. All SSF units were operated at a filtration rate of 0.3 m/h which was always preceded by a first day at 0.2 m/h following cleaning of fabrics and/or scraping sand. However, during the first week of experimentation period, all the SSF units were set at a rate of about 0.05 m/h which was gradually increased up to 0.3 m/h over seven days in order to allow for maturation.

At the end of the filter runs, about 40 mm of sand was scraped from the reference unit (i.e. AFM2) in order to ensure removal of the majority of the deposited impurities. In most cases, clean sand was refilled after scraping. For the fabric protected SSF units, depending on whether the capture of most of impurities occurred in the fabrics or in the top sand layer, either the fabrics alone or both the fabrics and the top sand layer were cleaned. In this case, clean sand was always refilled prior to restarting the units.

4.4.1 Filter Media Parameters Variation

It can be seen from tables 1.2 and 4.1 that the NWF samples chosen for this field test programme covered a very wide range of fabrics commercially available in the UK in terms of porosity and specific surface. For example, fabric lab. No. 44 represents the highest specific surface in table 1.2. While lab. No. 32 represents one of the three lowest specific surface, lab. No. 55 represents the top range of the intermediate specific surface NWF in table 1.2 . In terms of porosity, fabric lab. No. 32 was the most porous while lab. No. 44 was one of the least porous amongst the non-spunbonded NWF. In terms of nominal fabric thickness, the ratio of the thickest to the thinnest nominal NWF used was about 13.

As regards the variation of fabric properties, a set of three units i.e. AFM1, AFM4 and AFM5 were provided with a comparable total thickness (13 mm) of multiple or single layer NWF such that upon operation at a similar filtration rate, the performance of the three fabrics could be directly compared. The SSF unit AFM2 was used as a control/reference and therefore the conventional SSF sand bed of 480 mm depth was provided as a sole filter medium. In order to assess the influence of variation of total thickness of NWF, unit AFM3 was provided with two layers of lab. No.32 while AFM6 was provided with only 5 layers of lab. No. 44.

4.5 Results

The results of field tests are discussed in three main sections; the first is the hydraulic performance and the others are water quality improvements/changes and SSF sand bio-chemical properties. For the SSF units protected by fabric lab. No. 32 (i.e. AFM3 and AFM5), at the end of the filter runs both the fabric and the top sand layer had to be cleaned due to penetration of substantial amounts of impurities into the sand bed. However, for the SSF units protected by fabrics lab. No. 44 and 55 (i.e. AFM1, 4 and 6) there was no need to clean the sand bed at the end of the filter runs because most of the impurities were captured in the fabrics. These observations were confirmed by the head loss data.

4.5.1 Hydraulic Performance

4.5.1.1 Filter Run Time - Table 4.2 gives a summary of filter run times attained by the SSF units. Besides the differences in total fabric thicknesses of AFM1 and AFM6, their hydraulic behaviour was very similar and by the end of the field test period the top fabrics were completely blinded. Clearly, the table of filter runs shows a gradual decrease in length of filter run time for both SSF units. Although the top fabric of AFM4 did not show the tendency of blocking as early as AFM1, towards the end of the field test programme it could not sustain the rate of 0.3 m/h. Moreover, even considering the period of July/August 1986 only, the NWF lab. No. 44 and 55 did not increase the filter run time of fabric protected SSF units at all. However, on the basis of the mean filter run times, while

Table 4.2 Filter Run Times

SSF UNIT	FILTER MEDIA	NUMBER OF FILTER RUNS COMPLETED	SUCCESSIVE RUN TIMES (DAYS)	MEAN FILTER RUN (DAYS)			REMARKS
				July/August	September	October	
AFM1	10 layers of fabric lab. No. 44 over 480 mm sand.	20	6, 4, 3, 4, 3, 4, 4, 6, 4, 3, 3, 3, 3, 3, 2, 3, 2, 2, 3, 2 .	4	3	2	.Top fabric supported only 20 filter runs. .Upon removal of top fabric, the runs increased to 4 days. . Stopped on 24th October 1986.
AFM2	480 mm sand only (Reference)	13	6, 3, 4, 4, 5, 4, 2, 10, 9, 10, 5, 7, 6 .	4	8	6	.During high algae blooms and high aquatic life prescence, filter run time equal to AFM1. .Mean run time is 6 days.
AFM3	2 layers of fabric lab. No. 32 over 480 mm sand.	5	25, 25, 11, 32 and 18^* in that order.				.Shortest filter run occured during algae blooms and high aquatic life in water. .No reduction of filter run length with time. .Stopped on 27th October 1986. .Mean run time is 22 days .Premature end of filter run.
AFM4	13 layers of fabric lab. No. 55 over 480 mm sand.	18	8, 4, 3, 2, 3, 3, 4, 4, 6, 3, 5, 3, 3, 2, 3, 3, 2, 2 .	4	4	2	.In September, wide run time length variations were not uncommon. .Upon removal of top fabric,an increase to 9 days occured. .Stopped on the 27th October 1986
AFM5	Single layer of fabric lab. No. 32 over 480 mm sand	6	10, 9, 5, 6, 21, 24 in that order.				.Run times heavily influenced by raw water quality. .No decrease of run time. . Stopped on the 27th October 1986. . Mean run time is 18 days
AFM6	5 layers of fabric lab. No. 44 over 480 mm sand.	19	5, 4, 5, 4, 7, 3, 5, 5, 6, 3, 3, 4, 3, 2, 3, 2, 2, 3, 2.	5	3	2	.Advantage of lower initial headloss allowed an additional day of run sometimes. . Run time fell to 1 day later. . Stopped on the 24th October 1986

the single layer fabric lab.No. 32 extended the run time by an average factor of 3, the double layer unit AFM3 extended the run time by an average factor of 3.7 . Besides these substantial extensions of filter run time, the NWF lab.No. 32 could not stop penetration of impurities into the sand bed.

4.5.1.2 Filter Head Loss

In general the distribution of head loss in the filter beds was such that the SSF units protected by lab. No.44 and 55 showed that the majority of head loss was registered in the fabrics (i.e. by manometer No.2) . The initial head loss of these fabrics tended to increase with time probably due to successive blinding of the pores . SSF units protected by lab.No. 32 (AFM3 and AFM5) showed negligible headloss through the fabrics and most of the head loss was registered in manometer No. 3. This was due to penetration of impurities into the top layer of sand. Figs. 4.15 and 4.16 show typical head loss distribution in AFM1 which was provided with 10 layers of lab. No. 44 . Note the contribution of manometer No.2 indicating effective protection by the fabric. Figs. 4.17 and 4.18 show typical head loss distribution in AFM2 (the reference). Note that while Fig.4.17 shows the head loss during the filter run which was restarted without refilling the sand after scraping, Fig. 4.18 represents the same for the case when new sand was refilled. Fig. 4.19 gives a typical filter

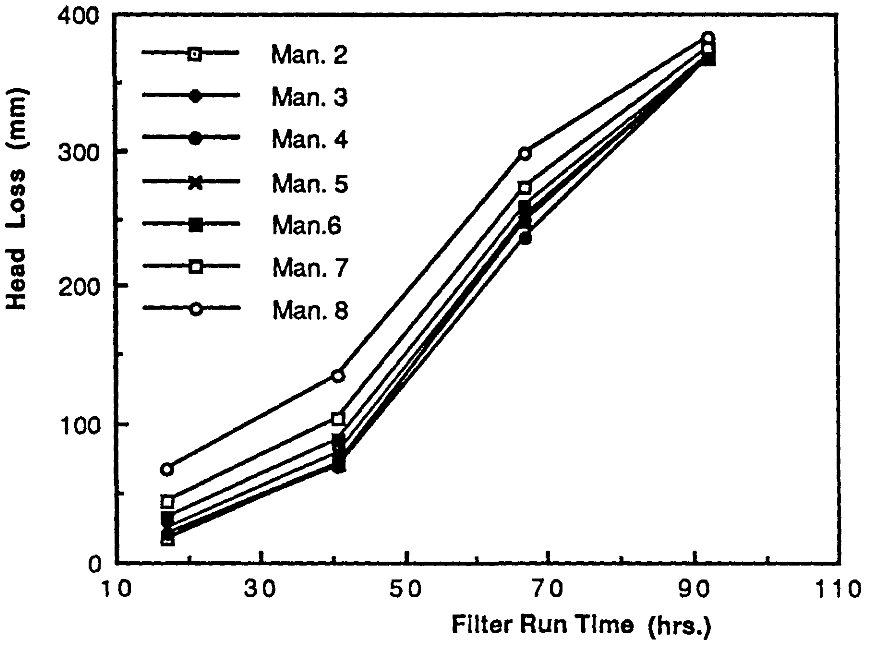


Fig. 4.15 AFM1 Filter Head Loss (Run 2) ·

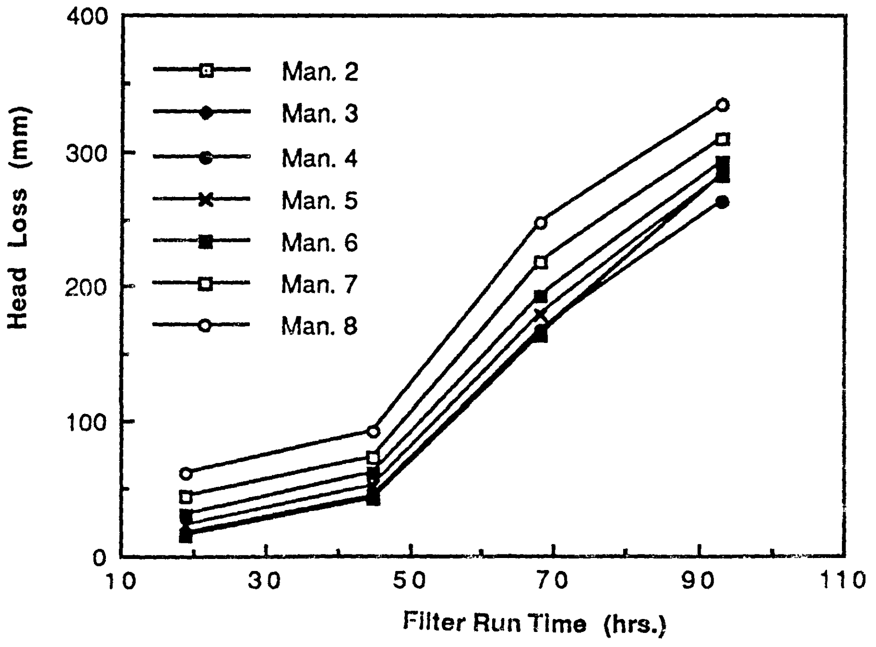


Fig. 4.16 AFM1 Filter Head Loss (Run 6) ·

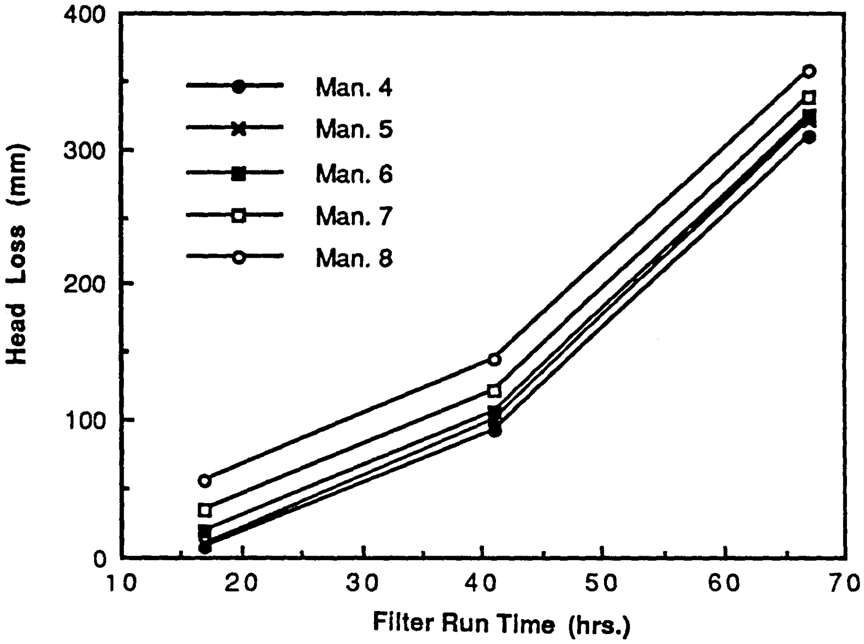


Fig. 4.17 AFM2 Filter Head Loss (Run 2).

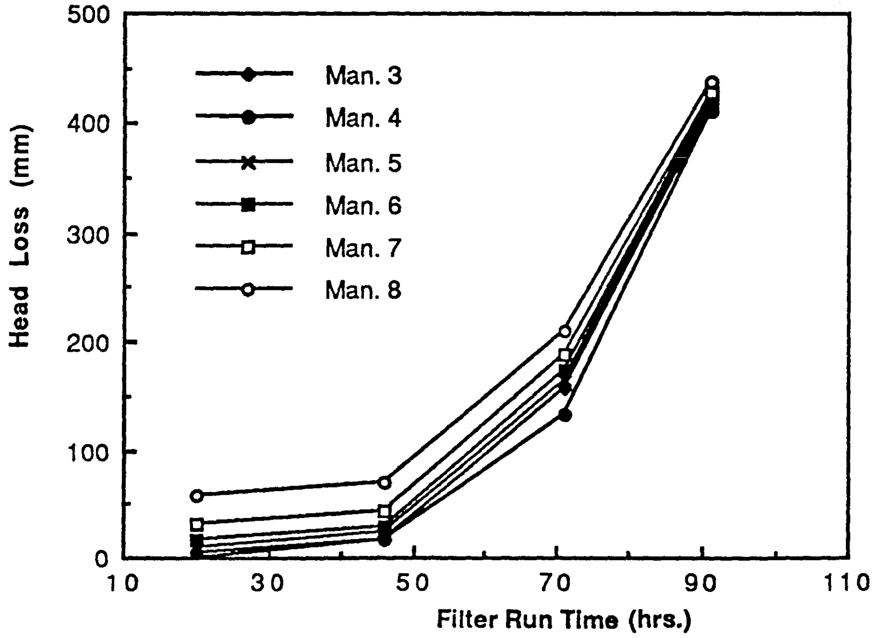


Fig. 4.18 AFM2 Filter Head Loss (Run 3).

head loss distribution for AFM4 with the manometer tube No.2 also indicating substantial protection of the sand bed. Fig. 4.20 and 4.21 show a typical head loss pattern in AFM5 provided with a single layer of lab. No. 32. Note the negligible contribution of manometer No.2 to head loss in this case.

4.5.1.3 Changes in Hydraulic Characteristics of the NWF

To establish the extent of changes in the hydraulic characteristics of NWF at the end of the field tests, samples of cleaned and dried top fabrics lab. No. 44, 55 and 32 from AFM1, AFM4 and AFM5, respectively, were subjected to hydraulic conductivity tests carried out in an identical manner to the experiments reported in section 3.3. Table 4.2 gives the hydraulic conductivity of the virgin and used NWF.

Table 4.3 Fabrics Hydraulic Conductivity

SSF Unit	Fabric Lab. No.	Hydraulic Conductivity(mm/s)		Decrease by Factor of
		Virgin	Used	
AFM1	44	0.49	0.036	14
AFM4	55	1.51	0.026	58
AFM5	32	47*	48*	-

*At an approach velocity of 0.5 m/h only.

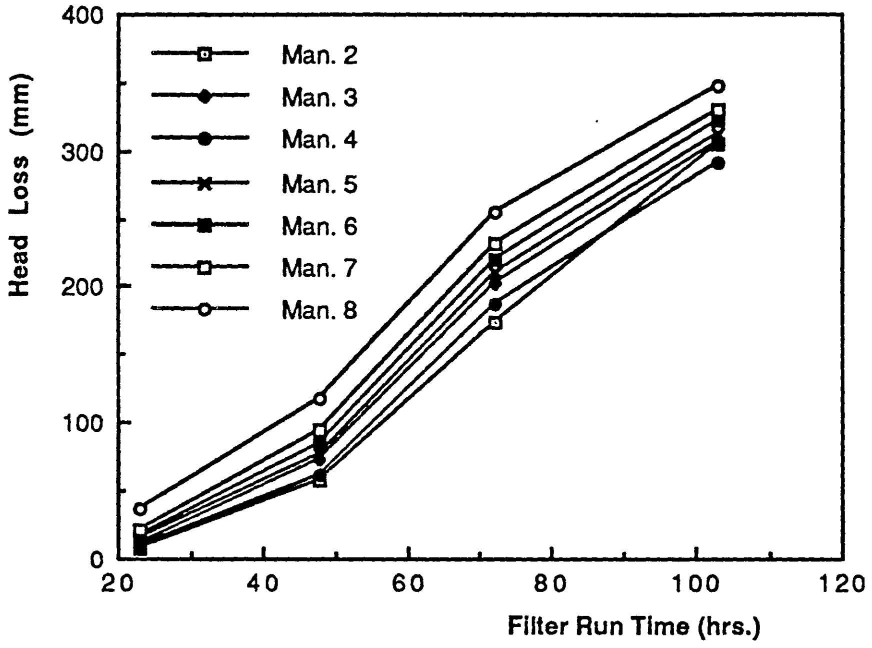


Fig. 4.19 AFM4 Filter Head Loss (Run 7) .

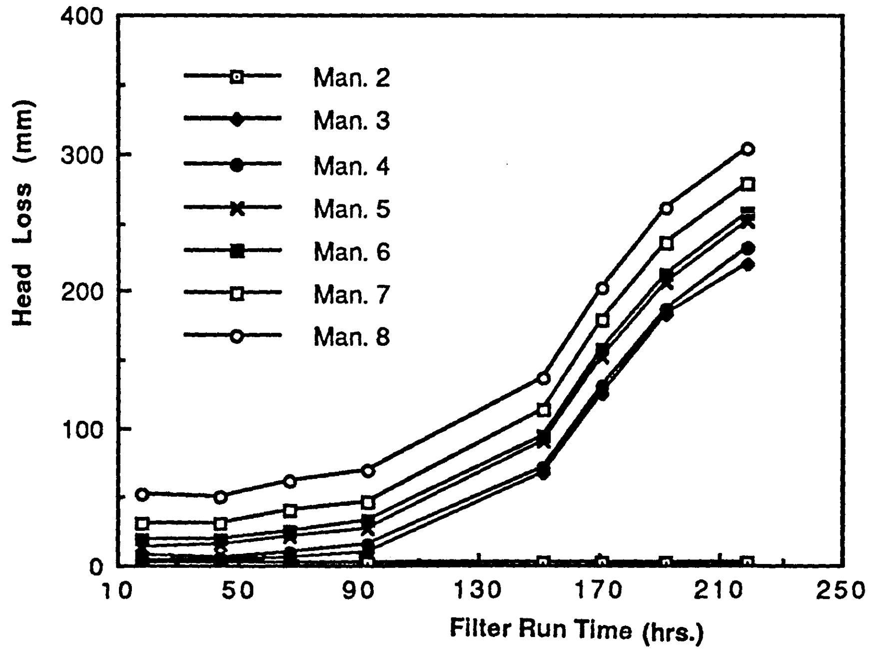


Fig. 4. 20 AFM5 Filter Head Loss (Run2).

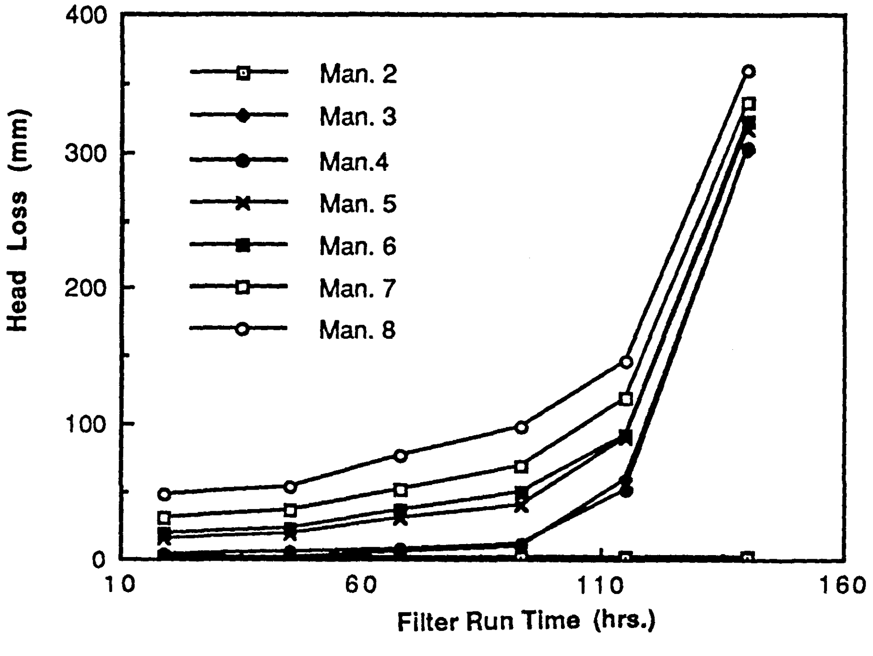


Fig. 4.21 AFM5 Filter Head Loss (Run 4).

4.5.2 Water Quality Improvements/Changes

In this section, the comparisons of water quality performances are not correlated with the progress of filter runs due to the fact that the filter run lengths of most of the units were very short. From table 4.2, it can be seen that with exception of a few filter runs of units AFM3 and AFM5, the mean filter run times never exceeded one week. This observation justified the assumption that the differences in performance due to the actual stage of the filter run would not have been substantial.

4.5.2.1 Temperature - During the field test programme, water temperature in SSF units which was taken at approximately the same time of the day ranged from 11.5 to 24.0 ^{o}C. Similar temperatures were recorded for the main works supernatant water. During this period the mean water temperature was 16.7 ^{o}C.

4.5.2.2 pH - During this period, the inlet water pH varied from 8.2 to 8.6 units only thus showing a more or less stable bio-chemical characteristics. No clear correlation of pH values with the intensity of algae in the SSF units was apparent.

4.5.2.3 Turbidity - The inlet water turbidity ranged from 0.7 to 1.7 NTU with maximum turbidity dominating the first week of August. Upon excluding the first week during which time the SSF units were maturing, filtrate turbidity levels were as indicated in table 4.4 . From the observed mean turbidity results, the differences in treatment performance with respect to turbidity were insignificant. Fig. 4.22 shows the turbidity removal in the SSF units.

Table 4.4 SSF Filtrate Turbidity

SSF Unit	Turbidity Range (NTU)	Mean Turbidity NTU	RSD (%)
AFM1	0.10 - 0.32	0.19	30
AFM2	0.10 - 0.34	0.18	29
AFM3	0.11 - 0.34	0.19	27
AFM4	0.11 - 0.36	0.19	27
AFM5	0.12 - 0.29	0.19	23
AFM6	0.11 - 0.32	0.18	24

4.5.2.4 Bacteriological Analysis - Tables 4.5 and 4.6 give the presumptive coliform and Faecal coliform(E.Coli) counts, respectively, for the inlet water and the SSF filtrates enumerated during the field test programme. The presumptive coliform counts in inlet water ranged from 24 to 760 per 100 ml. while the faecal coliform counts ranged from 3 to 200 per 100 ml. Figs. 4.23 and 4.24 show the coliform and E.Coli counts in the inlet water and SSF filtrates. Note the increase in the inlet water counts after 80 days.

4.5.2.5 Water POC and Chl-a - The inlet water POC varied from 269 to 817 mg C/m^3 while Chl-a varied from 2.08 to 21.2 mg/m^3. The mean inlet water POC was 455.3 mg C/m^3 (RSD = 37%) and the mean Chl-a was 8.94 mg/m^3 (RSD=65%). Figs. 4.25 and 4.26 show the removal of POC and Chl-a from

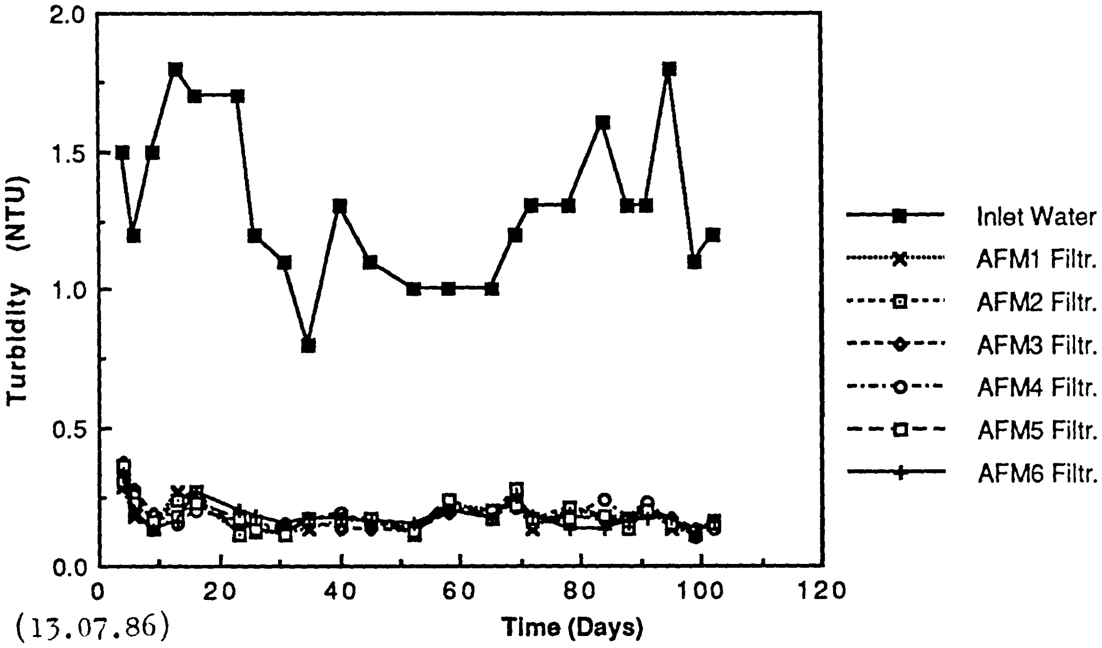


Fig. 4.22 Turbidity Removal in SSF Units.

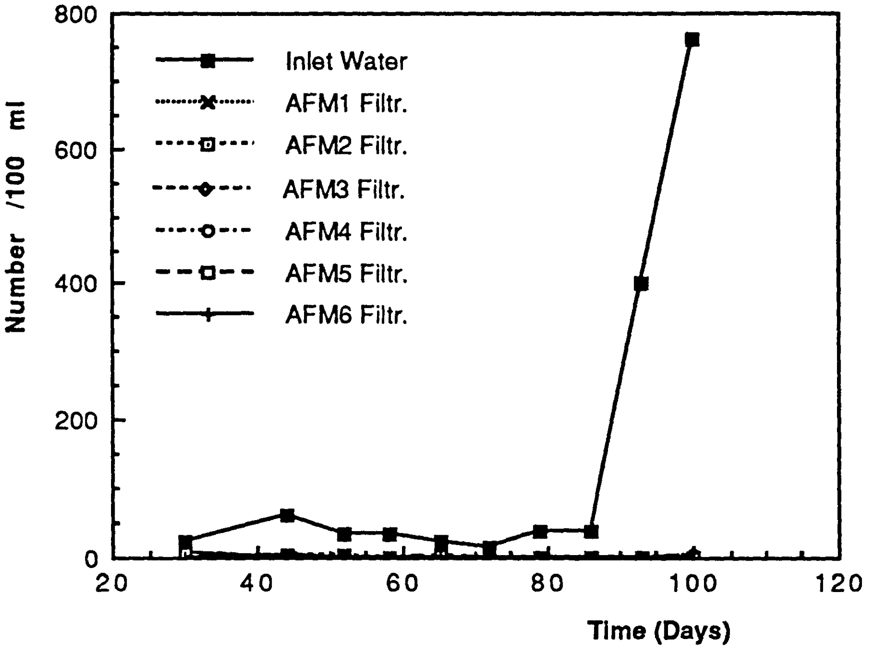


Fig. 4.23 Presumptive Coliform Counts.

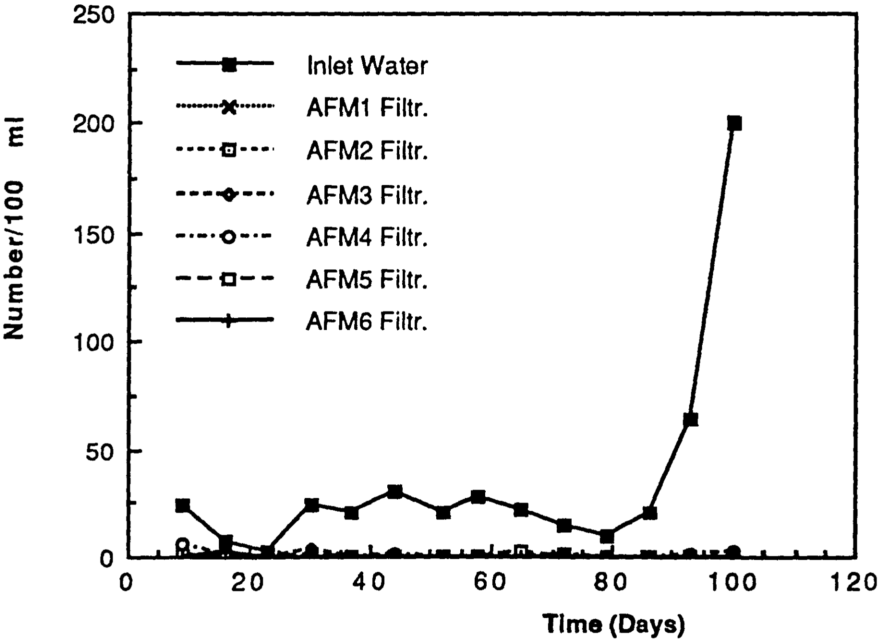


Fig. 4.24 Presumptive E. Coli Counts.

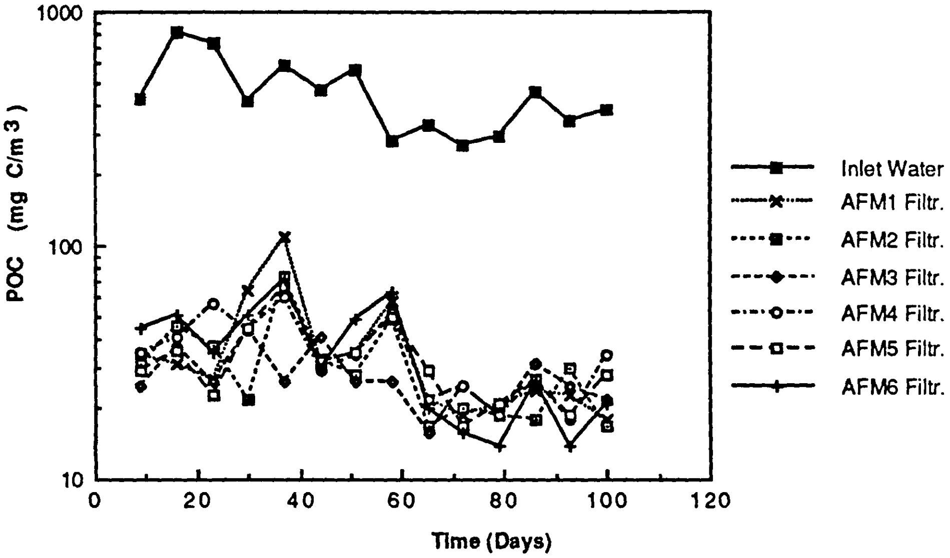


Fig. 4.25 Water POC Removal in SSF Units.

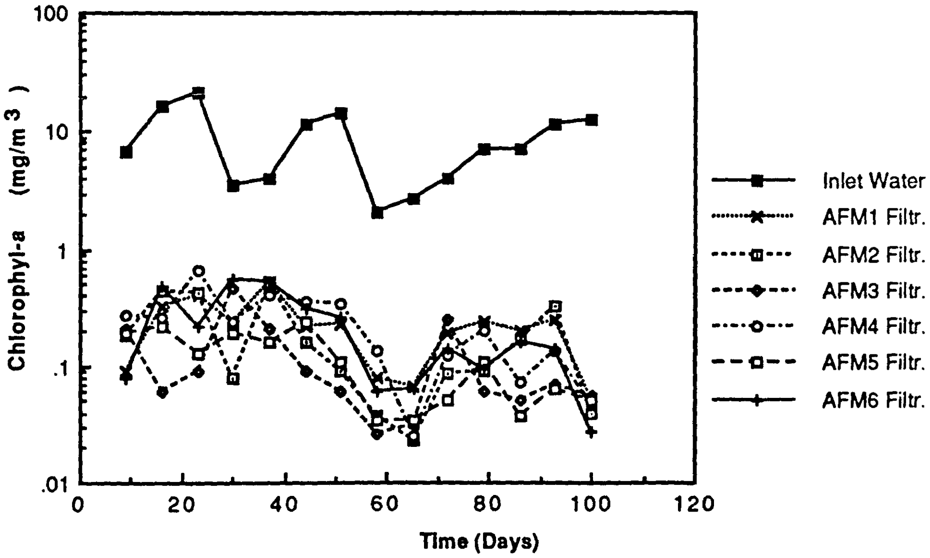


Fig. 4.26 Water Chl - a Removal in SSF Units.

water in the SSF units, respectively. The vertical axes are drawn in log scale in order to show the differences more clearly. Table 4.7 gives the mean POC and Chl-a percentage removals in the SSF units. All six units showed very good removals i.e $\geqslant 92\%$ for POC and $\geqslant 96\%$ for Chl-a.

Table 4.5 Presumptive Total Coliforms

Date	Numbers/100 ml.						
	Inlet	AFM1	AFM2	AFM3	AFM4	AFM5	AFM6
13/08/86	24	9	0	8	7	6	0
27/08/86	62	0	2	0	1	0	2
04/09/86	36	0	2	0	0	0	0
10/09/86	36	0	0	0	0	1	0
17/09/86	24	0	0	0	1	2	0
01/10/86	40	0	0	0	0	0	0
08/10/86	38	1	0	0	0	0	1
15/10/86	400	0	0	0	1	0	0
22/10/86	760	0	0	2	3	0	0

Table 4.6 Presumptive Faecal Coliforms

Date	Numbers/100 ml						
	Inlet	AFM1	AFM2	AFM3	AFM4	AFM5	AFM6
23/07/86	24	0	0	1	6	1	0
30/07/86	7	1	1	0	1	0	2
06/08/86	3	0	0	0	0	0	0
13/08/86	24	0	0	4	1	0	0
20/08/86	20	0	0	0	0	0	0
27/08/86	30	0	0	0	1	0	0
04/09/86	21	0	0	0	0	0	0
10/09/86	28	0	0	0	0	0	0
17/09/86	22	0	0	0	0	2	0
24/09/86	14	0	1	0	0	0	0
01/10/86	10	0	0	0	0	0	0
08/10/86	20	0	0	0	0	0	0
15/10/86	64	0	0	0	1	0	0
22/10/86	200	0	0	0	3	0	0

Table 4.7 POC and Chl-a Removal

SSF Unit	POC Removal Mean (%)	POC Removal RSD (%)	Chl-a Removal Mean (%)	Chl-a Removal RSD (%)
AFM1	92	6	97	3
AFM2	93	4	98	3
AFM3	93	2	98	2
AFM4	92	4	97	3
AFM5	92	4	98	2
AFM6	92	5	96	5

4.5.2.6 Particle Capture Efficiency - The particle size distribution of water and SSF filtrates enabled volume and number removal efficiencies to be evaluated as indicated on table 4.8. The results were evaluated on the basis of twelve or more samples analyzed. All SSF units showed good removal efficiency (i.e. $\geqslant$ 92%). To some extent particle removals seem to be related to the length of filter run times. The data shows very small differences in performance between the units. Probably the presence of a depth of 480 mm of sand underneath the fabrics obscured the actual differences (if any).

Table 4.8 Total Particle Number/Volume Removal

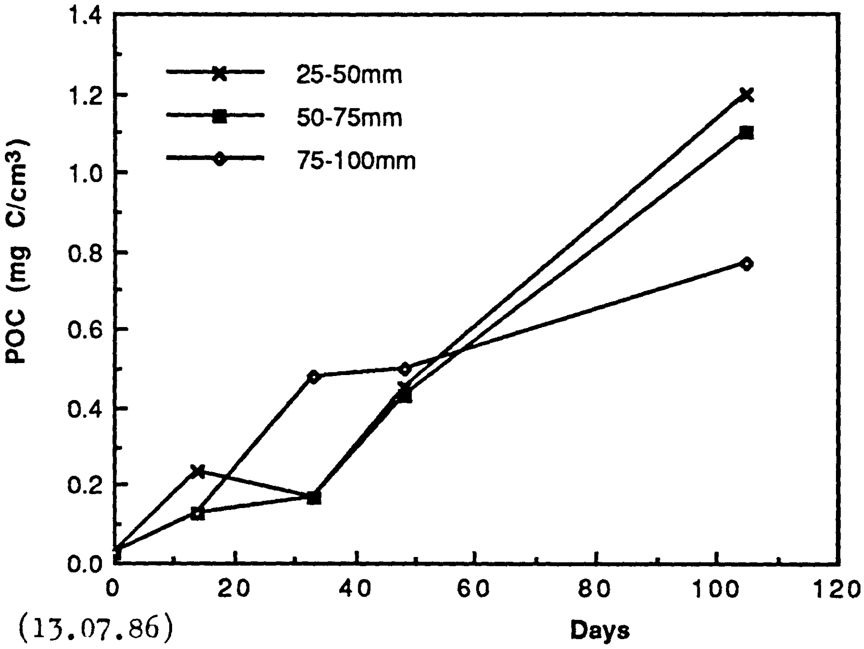
SSF Unit	Total Number Removal Mean (%)	Total Number Removal RSD (%)	Total Volume Removal Mean (%)	Total Volume Removal RSD (%)
AFM1	92	7.0	92	7.0
AFM2	95	2.2	95	3.1
AFM3	95	3.7	94	3.7
AFM4	94	5.0	93	5.3
AFM5	95	4.5	94	5.1
AFM6	94	5.2	94	4.7

4.5.3 SSF Sand Bio-chemical Properties

The mean characteristics of clean unused sand evaluated on the basis of triplicated sand samples were as follows:

POC = 0.027 mg C/cm^3 sand (RSD = 17.0 %)
Chl-a = 0.046 mg/cm^3 sand (RSD = 2.2 %)
Silt Content = 0.32 μ g/cm^3 sand (RSD = 4.8 %)
(Dry)

4.5.3.1 Sand POC - Fig. 4.27 through 4.30 show the POC variation in the SSF beds sampled at the end of filter runs. Fig 4.27 shows POC accumulation in AFM2 sand bed for the depth of 25 - 100 mm. The top 25 mm depth of sand has been left out because it was completely removed at the end of every filter run. However, the pattern in the three layers underneath was such that POC increased with time in decreasing order with depth. A maximum POC value attained in the 25 - 50 mm sand layer was 1.2 mg C/cm^3. Fig. 4.28 shows a slow build up of POC in AFM1 until beyond 80 days after which it fell in the top 50 mm while in the bottom 50mm it continued to increase. This observation coincided with the begining of cold weather at the pilot plant site. A maximum POC value of 0.35 mg C/cm^3 was recorded. Fig.4.29 shows negligible changes of POC level in AFM4 until beyond 65 days when increases of POC were nearly in decreasing order with depth of sand layers. A maximum POC value of 0.56 mg C/cm^3 was recorded. Fig. 4.30 shows



(13.07.86)

Fig. 4.27 AFM2 POC Variation in Sand.

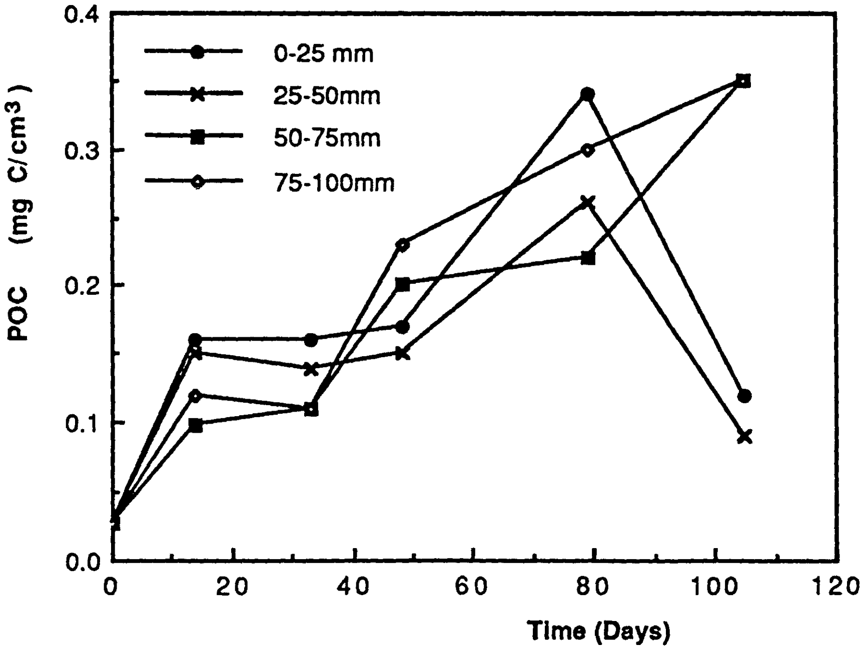


Fig. 4.28 AFM1 POC Variation in Sand.

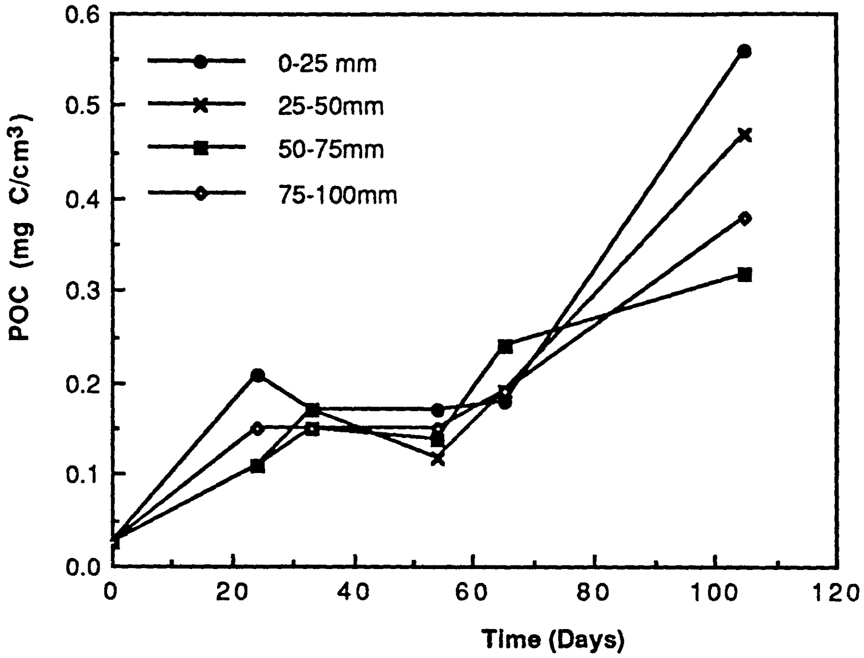


Fig. 4.29 AFM4 POC Variation in Sand.

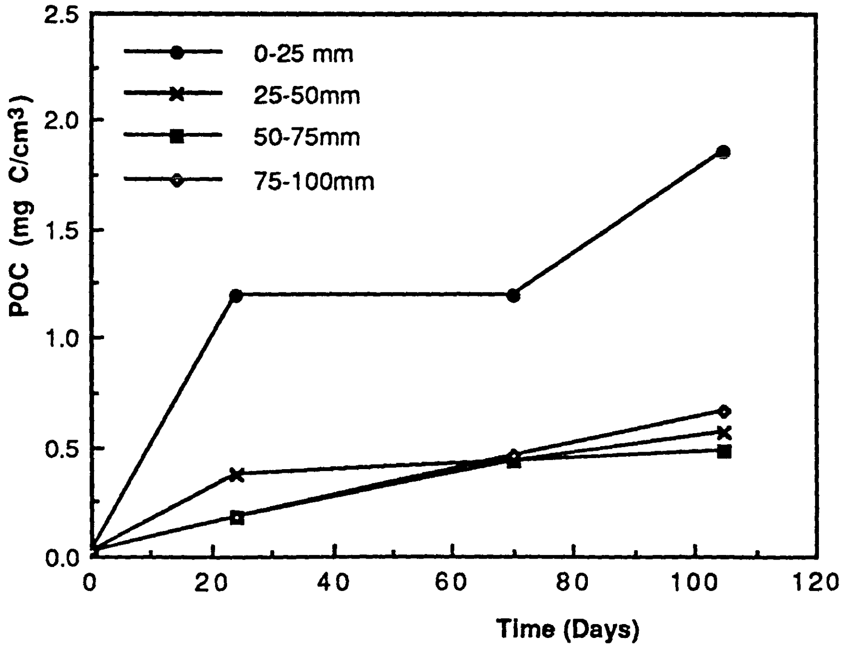


Fig. 4.30 AFM3 POC Variation in Sand.

bigger increases in the top 25 mm of sand in AFM3 besides being scraped at the end of each filter run. This might have been a consequence of the longer filter run times observed. The maximum recorded POC in AFM3 and AFM5 were 1.86 and 1.05 mg C/cm^3, respectively.

4.5.3.2 Sand Chl-a - Figs. 4.31 through 4.34 show the variation of sand Chl-a in the SSF beds sampled at the end of filter runs. Fig. 4.31 shows a distribution almost similar to POC in AFM2 with a maximum Chl-a of about 36 mg/cm^3 in the 25 -50 mm depth of sand during the last filter run. The pattern of accumulation of Chl-a in AFM1 shown on Fig. 4.32 was again very similar to POC with a maximum value of only 0.72 mg/cm^3. In Fig. 4.33 the pattern is again similar to POC such that until after 65 days the increase of Chl-a in AFM4 is negligible. A maximum Chl-a of 15.8 mg/cm^3 was recorded at the end. For AFM3 (see Fig. 4.34), the Chl-a distribution closely follows that of POC . The recorded maximum Chl-a values for AFM3 and AFM5 were 35.3 and 36.2 mg/cm^3, respectively.

4.5.3.3 Sand Silt Content- Figs. 4.35 through 4.39 show the variation of silt content in SSF sand beds. Fig. 4.35 shows the silt content variation in AFM2 for the 25-100 mm layers of sand. The pattern shows increasing silt content in all layers. The magnitudes are in decreasing order with depth. A maximum silt content recorded was 8.16μg/cm^3 sand in this case. Fig. 4.36 shows the variation of silt

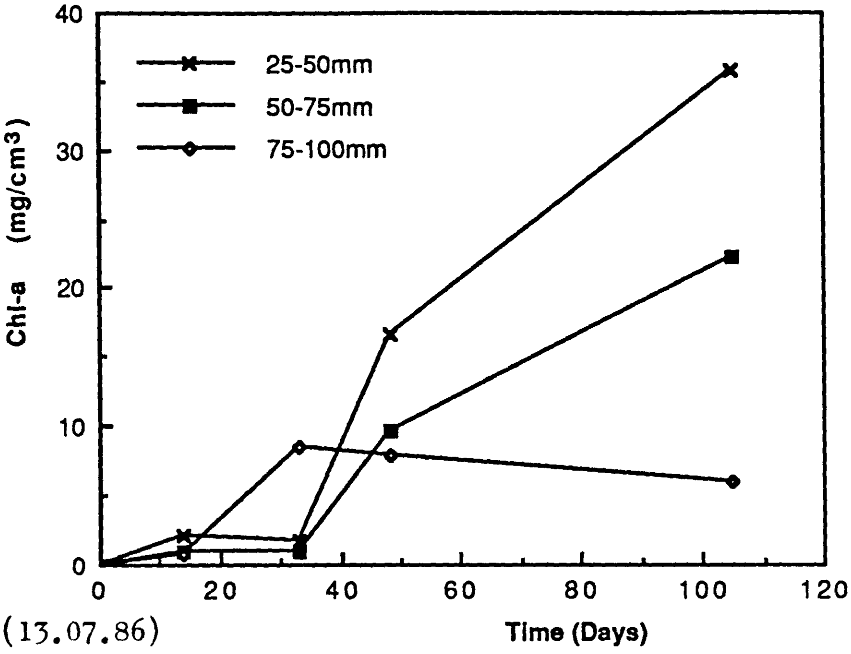


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Fig. 4.31 AFM2 Chlorophyll-a Variation in Sand.

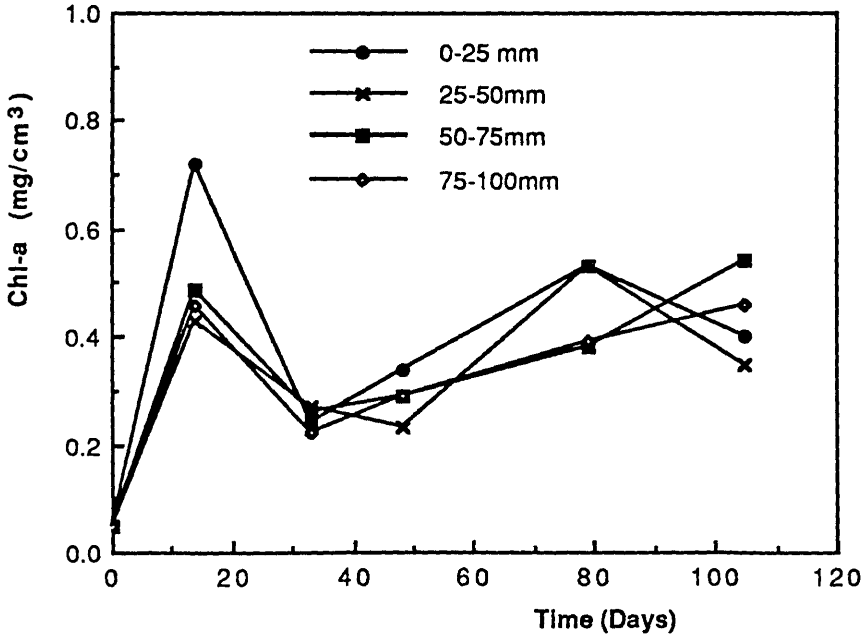


Fig. 4.32 AFM1 Chlorophyll-a Variation in Sand.

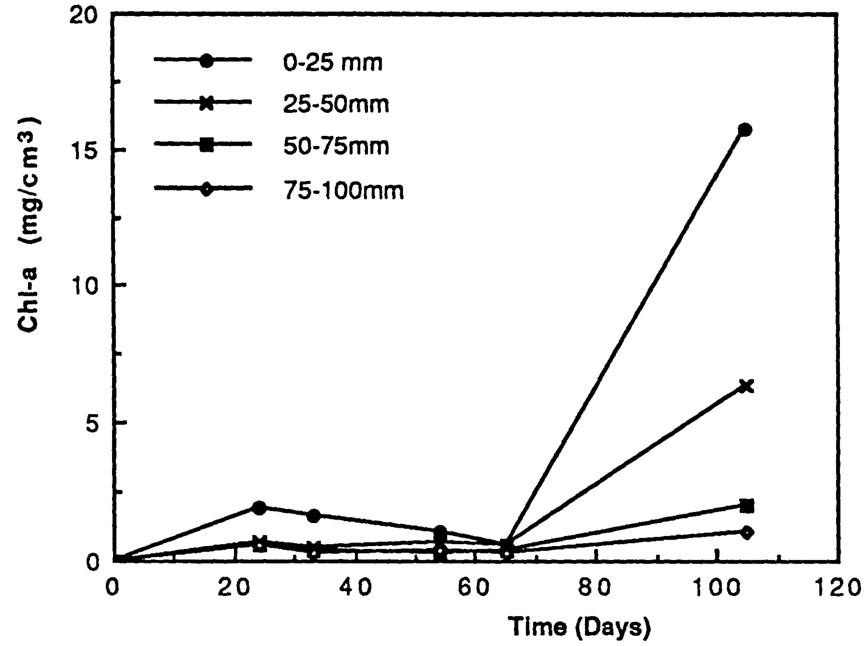


Fig. 4.33 AFM4 Chlorophyl-a Variation in Sand.

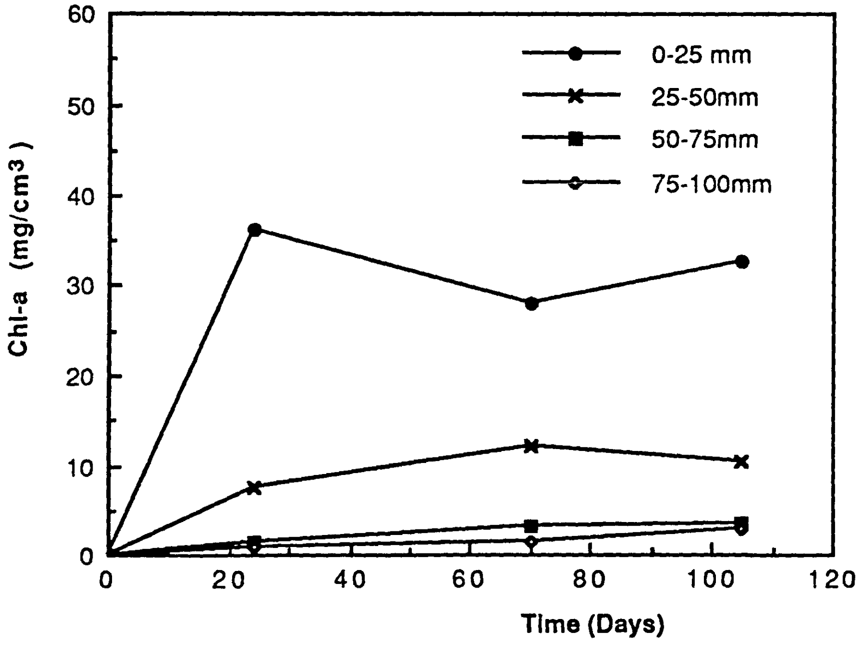


Fig. 4.34 AFM3 Chlorophyl-a Variation in Sand.

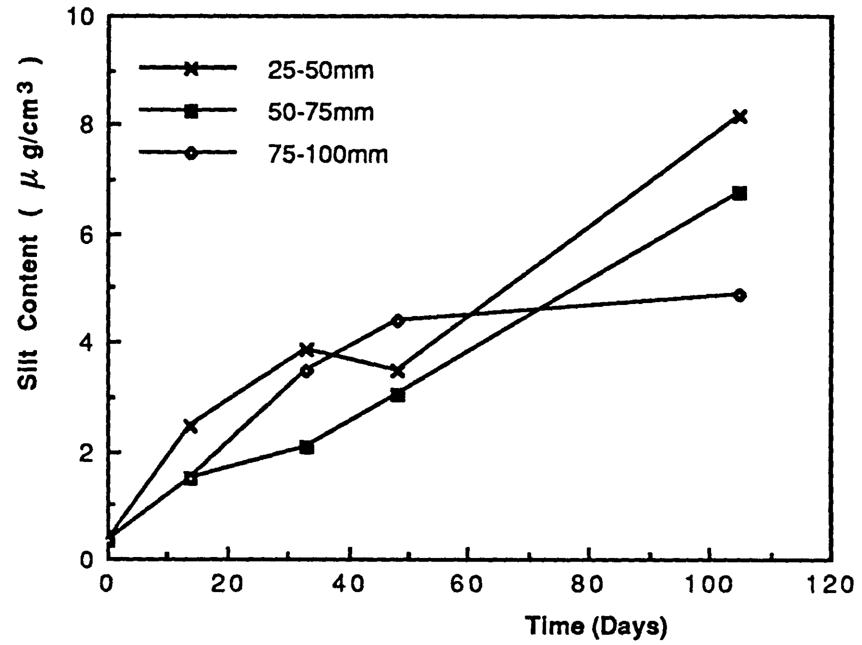


Fig.4.35 AFM2 Silt Content in Sand.

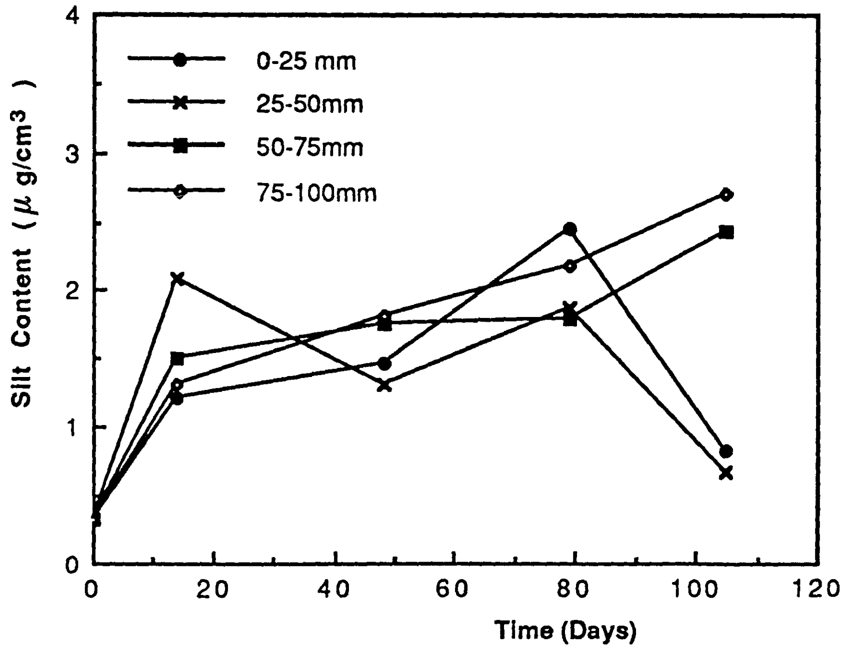


Fig. 4.36 AFM1 Silt Content in Sand.

content in AFM1 which builds up gradually in all layers except during the last filter run for the top 50 mm of sand. The maximum silt concentration was 2.70 μ g/cm^3 sand. Fig. 4.37 shows the variation of silt concentration in AFM4, the overall trend is increase of silt content in all four layers. The maximum silt content during the last run was 3.87 μ g/cm^3 sand. Figs.4.38 and 4.39 show the silt content variation in units protected by fabric lab No. 32. For unit AFM3, the general trend was that of very big increases in the top 25 mm accompanied with moderate changes in lower layers. For AFM5, the top 25 mm of sand is excluded from the graph (Fig 4.39) due to the considerable fluctuations resulting from scraping it at the end of the filter runs. The accumulation was in decreasing order with depth. At the end, the maximum silt content of 10.7 and 7.7 μ g/cm^3 sand were recorded in AFM3 and AFM5, respectively.

4.6 Discussion of Results

4.6.1 Hydraulic Performance

The gradual decrease of the filter run time of NWF lab. No. 44 and 55 to the extent of ultimately not being able to sustain the rate of 0.3 m/h even for a day meant besides their exceptional ability to protect the sand beds from most impurities, these fabrics were not regarded to be suitable for application under the operational conditions studied. However, besides these observations, it was

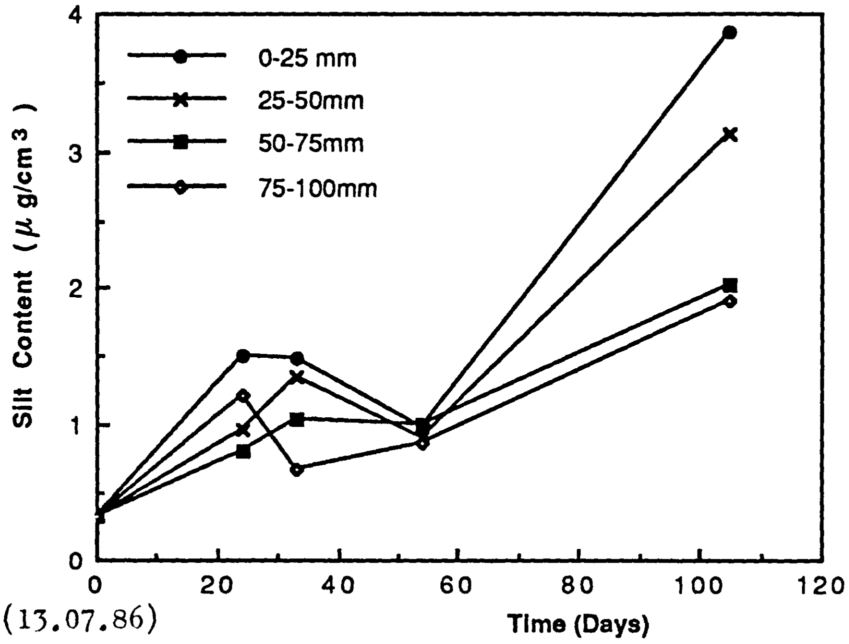


Fig. 4.37 AFM4 Silt Content in Sand.

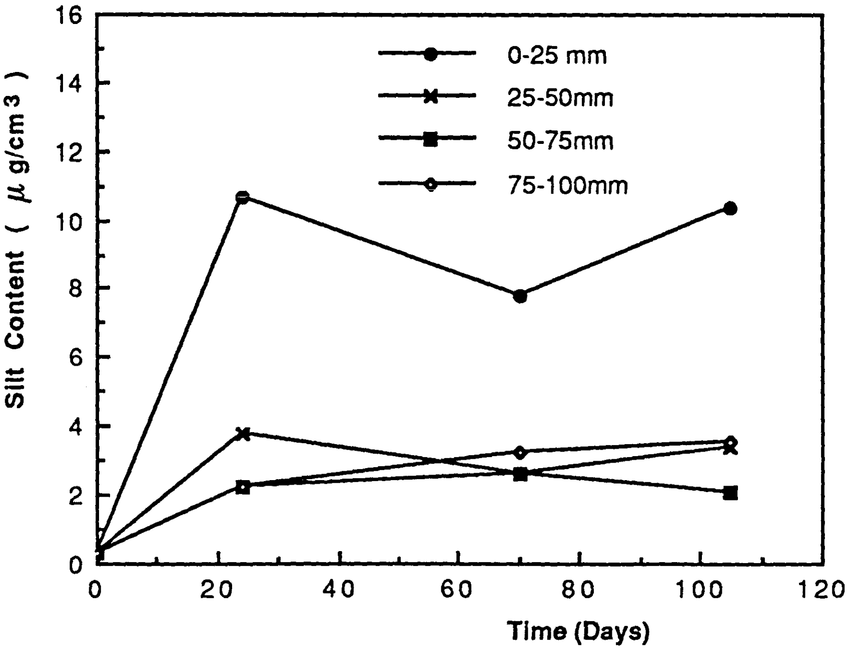


Fig. 4.38 AFM3 Silt Content in Sand.

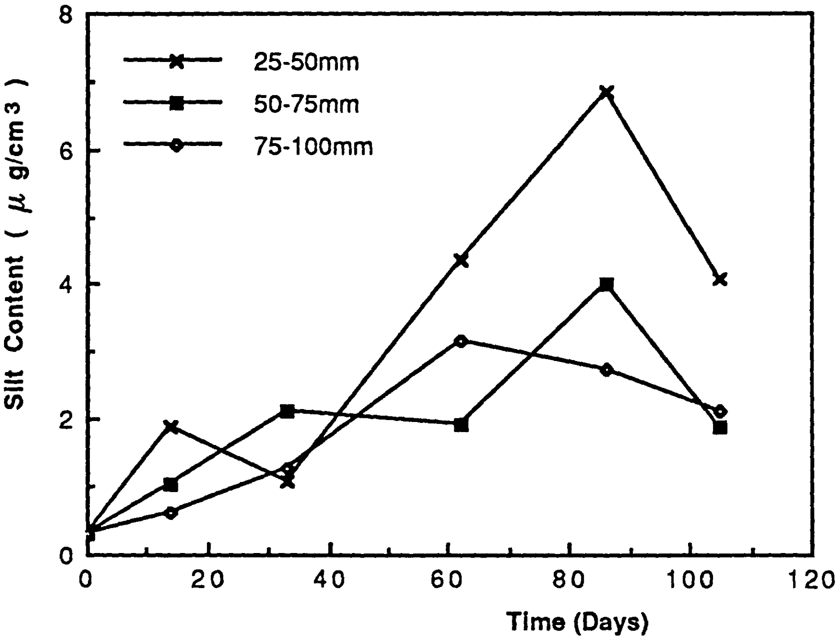


Fig. 4.39 AFM5 Silt Content in Sand.

decided to test the performance of fabric lab. No. 44 in the next set of field tests before making a final decision on its potential for fabric protection of conventional SSF. On the basis of the mean filter runs indicated in table 4.2, the filter run time of AFM3 and AFM5 was extended by factors of 3.7 and 3.0, respectively. The filter run time extension of AFM5 is comparable to that reported by Wheeler et al (81). The differences in mean filter run times of the single and double layer NWF lab.No. 32 was probably due to the higher overall particle capture efficiency of the latter as a result of the bigger depth. It is also anticipated that multi-layering increases the tortuosity of the paths through which particles in suspension have to travel as a result increasing the probability of interception (106).

Filter head loss results showed that fabrics lab. No. 44 and 55 were very effective in protection of the sand beds from most of the impurities and therefore head loss across the fabrics contributed a very big proportion of the total head loss in each case. However, in conformity with laboratory findings, NWF lab. No. 32 registered a negligible filter head loss besides keeping the SSF beds running for up to one month. This led to the consideration that its high storage ability (due to high porosity) and very low head loss development could probably be exploited in combination with other denser fabrics for protection of SSF sand beds in multi-layer configurations.

Table 4.3 shows that fabric lab. No. 32 which is one of the most porous NWF selected for the field tests, did not show any changes in its permeability after more than three months of use. This was consistent with field observations regarding its head loss where the end of the runs were caused by blockage of sand underneath the fabric(s). The substantial decrease of the permeability of fabric lab. No. 55 in comparison to lab. No. 44 might have been dependent upon the extent of washability. In addition, the excessive abrasion of fibres after several successive washings might have led to changes in the physical characteristics of No. 55 which might have encouraged particles embedment in between the fibres. It must therefore be noted that mechanical and chemical properties of the fibre materials are important factors in selection of NWF for protection of SSF beds because of their role in dictating the most suitable fabric cleaning techniques.

4.6.2 Water Quality Improvements

Concerning the SSF filtrate turbidity, it was felt that obscurity of the differences in treatment performance (if any) might have been a result of the relatively low inlet turbidity coupled with the fact that the filtrate samples were taken after going through a depth of 480 mm of sand bed. As regards the bacteriological analysis, with exception of a few cases no E. Coli or Coliforms were detected in SSF filtrates and their removals were consistently more than 95%. Cases of detection of E. Coli or Coliforms occurred either immediately after cleaning or inadvertent flow disturbance of inlet water. The phenomenon of the NWF contaminating the SSF filtrates to the extent of recording higher bacteriological counts than in the inlet water observed after fabric cleaning at Wessex Water Authority (123) did not occur during this study. In general, the SSF units showed no significant differences in removal of bacteria.

With regard to the particle size analysis, as it was felt that the sampling of filtrates downstream of the SSF sand bed might also have obscured the differences in particle capture efficiency, it was therefore planned to take samples underneath the fabrics in the next set of experiments in order to have a better basis for distinction. From table 4.7 it is not easy to quantify with certainty the differences in performance of the six SSF units. However, there was a close correlation between the mean POC and Chl-a removals to the length of filter run time.

4.6.3 SSF Sand POC, Chl-a and Silt Content

The overall trend of POC was that of gradual accumulation in the sand bed in all units. This observation is similar to the findings of Toms et al (122). The extent of protection of SSF beds can be judged on the basis of the maximum recorded POC which were found to be 13, 21, 39, 44 and 69 times the clean sand value for AFM1, AFM4, AFM5, AFM2 and AFM3, respectively. This proved the superiority of fabric lab. Nos. 44 and 55 in protection of the sand beds. As regards Chl-a, the overall trend of build up was almost similar to POC and on the basis of the maximum recorded values which were 16 , 343, 767, 783 and 787 times the clean sand value for AFM1, AFM4, AFM3, AFM2 and AFM5, respectively, once again , the outstanding ability of lab. No. 44 to protect the sand from algal activity was demonstrated. Although there was a big difference between the protection ability of lab. No. 44 and 55, still the latter reduced Chl-a by more than half in comparison to the reference. In this case, the performance of the reference was similar to lab. No.32.

The extent of protection of the sand bed from silt deposition can be once again compared by relating the maximum recorded levels to the clean sand. On this basis units AFM1, AFM4, AFM5 and AFM3 were found to have 8, 12, 24 and 34 times more silt than clean sand, respectively. Once again the superiority of the NWF lab. No. 44 in protection of sand beds was established. In general the protection ability of all the fabrics studied was directly related to their specific surface as postulated in the second chapter. As a result of these findings, the next set of experiments was designed to optimize the performance of a lower range intermediate specific surface NWF ensuring extended run times and bed protection in addition to testing the performance of fabrics lab. No. 32 and 44 at 0.15 m/h for comparative purposes.

Chapter Five

5. OPTIMIZATION OF FIELD FILTRATION PERFORMANCE OF A SELECTED NWF.

These experiments were done between mid-November 1986 and end of March 1987 at the Ashford Common pilot plant after carrying out a number of plant modifications. The purpose of these experiments was to identify a middle range intermediate specific surface NWF which could protect conventional SSF sand beds from the majority of impurities and also substantially extend the filter run time. On the basis of the results obtained in the preceding chapter, it was decided to select a NWF with a specific surface lying somewhere between the fabrics lab. No. 55 and 32 . In order to prevent/minimize penetration, several multiple layers of the selected fabric were tested. Fabrics lab. No. 44 and 32 were used for comparative purposes. For this reason and also in order to test the performance at a lower filtration rate, two units were provided with a chosen configuration of each of these NWF.

5.1 Pilot Plant Modifications

Modifications of the pilot plant were done between the end of October and mid-November 1986. During this period, three main rehabilitation activities were done:

(i) Replacing sand in all the SSF units.

(ii) For all the fabric protected units, a sampling tube was connected on manometer No.2 to allow collection of water samples overnight from underneath the fabrics at a very slow rate (i.e. less than or equal to 0.15 m/h).

(iii) Cleaning up all filter components, pipes and the header tank and repair of all leaking/broken components.

During the second and third week of January 1987, severe winter temperatures resulted in extensive freezing of the pilot plant. Therefore the most vulnerable parts had to be insulated with an 105 mm thick layer of fibre glass loft insulation "supawrap" (Pilkington, UK).

5.2 Reservoir Water Source and Quality

During this period, the raw water was mainly drawn from the Queen Mary reservoir sometimes in combination with the Wraysbury reservoir. The maximum combined reservoir water POC and Chl-a were 1235 and 21.3 mg/m^3, respectively . The maximum micro-strainer filtrate POC and Chl-a were 732 and 10.3 mg/m^3, respectively . In the reservoirs, the dominant algae were diatoms and Blue greens. The main species identified were Stephanodiscus astraea, Asterionella sp. and Aphanizomenon sp. . Concerning the animal populations, the dominant groups were Copepods and Cladocerans .

5.3 Filter Media

The grading of sand used in SSF units was similar to that used in the field tests reported in the preceding chapter. As regards the fabrics used, table 5.1 gives the type and configurations used. The fabric lab. No. 27 was the middle range intermediate specific surface NWF selected for optimization. Reference should be made to table 1.2 for properties of this fabric. Note that the actual selection was based on identification of a NWF with a specific surface closest to 15,000 m^2/m^3 estimated to be the average intermediate specific surface on the basis of an assumption of 20,000 and 10,000 being the top and low ranges of the NWF listed in table 1.2 . An additional factor for final selection was the willingness of the manufacturers/suppliers to cooperate if necessary.

Table 5.1 NWF Installed in SSF Units

SSF Unit	Fabric Lab. No.	Number of Layers	Nominal Thickness (mm)	Total Fabric Thickness (mm)
AFM1	27	6	3.6	21.6
AFM2	None	-	-	-
AFM3	32	1	13	13
AFM4	27	4	3.6	14.4
AFM5	27	2	3.6	7.2
AFM6	44	5	1.3	6.5

While unit AFM2 continued to be used as a reference, the units AFM3 and AFM6 were provided with a single and five layers of lab. No. 32 and 44, respectively. In order to establish the number of layers of fabric lab. No. 27 required for proper protection of the sand beds, 2,4 and 6 layers were installed. The intention was to minimize the number of layers required so as not to make handling too difficult in practice and also to keep the investment costs of fabric protection as low as possible.

5.4 General Conduct of Tests

Before filling the units with sand, three samples of clean unused sand were taken in order to establish the initial POC and silt content. The pilot plant was commissioned on the 14/11/86 which was the reference day (day number zero) for water quality monitoring. To start with, all units were operated at a filtration rate of about 0.10 m/h for four days after which it was increased to 0.15 m/h . During the rest of the filter run time, the SSF units were operated at a constant rate of 0.15 m/h . The filtration rates were confirmed/adjusted daily.

5.4.1 Sampling Frequency and Analysis Methods

The parameters which were monitored included water temperature, turbidity, pH, bacteriological quality, particle size distribution, water POC and Chl-a, POC and silt content of sand profile samples. While only the inlet water samples were analyzed for pH and water temperature, turbidity, bacteriological quality, particle size distribution, water POC and Chl-a were analyzed for the inlet water and the six SSF filtrates. Temperature and turbidity were analyzed on a daily basis while the rest were analyzed once per week. POC and silt content of sand core samples were taken only at the end of the filter runs. The methods of analysis of all the parameters listed have already been described in the preceding chapter (section

4.2) . Filter head loss was monitored daily with the help of eight manometer tubes also described in the preceding chapter. Water temperature was taken at approximately the same time of the day.

5.5 Results

The results are discussed in four main sections. These are; hydraulic performance, water quality improvements/changes and SSF sand POC and silt content. In the fourth section a brief overview of washability aspects of the NWF used is given .

5.5.1 Hydraulic Performance

5.5.1.1 Filter Run Time - Table 5.2 gives the number of complete filter runs attained by the six SSF units during the period of experiments which started on the 14/11/86 and ended on the 23/03/87. A survey of the filter runs shows that the reference filter (AFM2) had an average filter run time of 56 days. As expected, this was the shortest run time since all impurities were captured on the sand grains. However, unit AFM6 with five layers of NWF lab. No. 44 having the highest specific surface extended the run time by a factor of 1.23. The single layer lab. No. 32 extended the filter run time by a factor of 1.61 while the double layer NWF lab. No. 27 extended it by a factor of 1.48. The four and six layers of NWF lab. No. 27 nearly doubled the filter run time of the SSF units protected. On the basis of the filter run time only, the differences in the performance of these two units (i.e. AFM1 & AFM4) was insignificant.

Table 5.2 Filter Run Times

SSF Unit	Filter Media	Filter Runs Completed	Filter Run Time (Days)	Remarks
AFM1	6 layers lab. No. 27 over 480 mm sand	1	113	Second run in 14th day
AFM2	480 mm sand only (reference)	2	54,57	Third run 14th day
AFM3	One layer lab. No. 32 over 480 mm sand	1	90	Second run 35th day
AFM4	4 layer lab. No. 27 over 480 mm sand	1	111	Second run 14th day
AFM5	2 layers lab. No. 27 over 480 mm sand	1	83	Second run 35th day
AFM6	5 layers lab. No. 44 over 480 mm sand	1	69	Second run 60th day

5.5.1.2 Filter Head Loss - Fig. 5.1 shows the head loss pattern of the first filter run of AFM2, the reference. The fact that manometer tube No. 3 shows a head loss atypical of surface filtration is likely to be due to the compaction of the sand bed to a level just below this tube after refilling the unit with clean sand following scraping. In this case, reference to manometer tube No. 4

as the surface tube would be a more correct approach. The fall of sand bed top level was also noted during scraping of sand at the end of the run. Note that after 20 days the rate of increase of head loss shot up. A comparison of Figs. 5.2 through 5.4 giving the head loss patterns during the first filter runs of AFM5, AFM4 and AFM1, respectively, shows that in conformity with fundamental filtration theories, there is a good correlation between the extent of protection of the sand beds and the number of NWF layers installed. Fig. 5.2 shows that as a result of penetration of a lot of impurities into the sand bed, the manometer tube No. 2 did not contribute much to the overall head loss. This confirmed that the two layers of NWF lab. No. 27 were not sufficient for acceptable protection. Nevertheless, the fast increase in head loss was delayed until beyond 50 days.

Fig. 5.3 shows that the four layers of fabric lab. No. 27 afforded a substantial protection of the sand bed. The particles which managed to penetrate through the four fabric layers might have accounted for the wider gap between manometer tubes No. 3 and 4 . On the other hand such long filter runs are characterized by very well established bio-chemical processes which might have led to air entrainment in one of the manometer tubes. Note the fact that the steep increase of head loss was delayed until beyond 90 days. Fig 5.4 shows that the sand bed was very well protected by the six layers of NWF lab. No. 27.

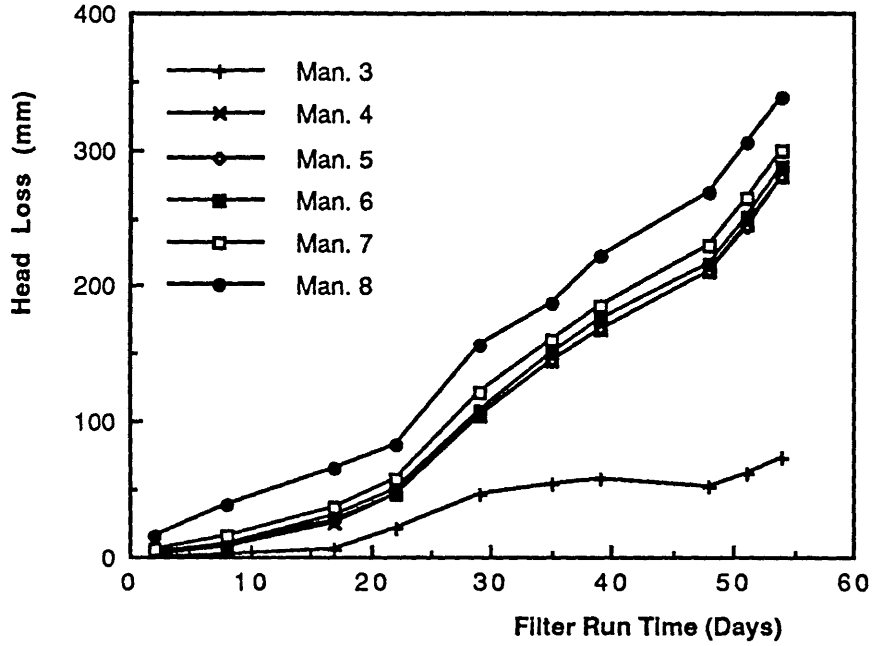


Fig. 5. 1 AFM2 Filter Head Loss (Run1) ·

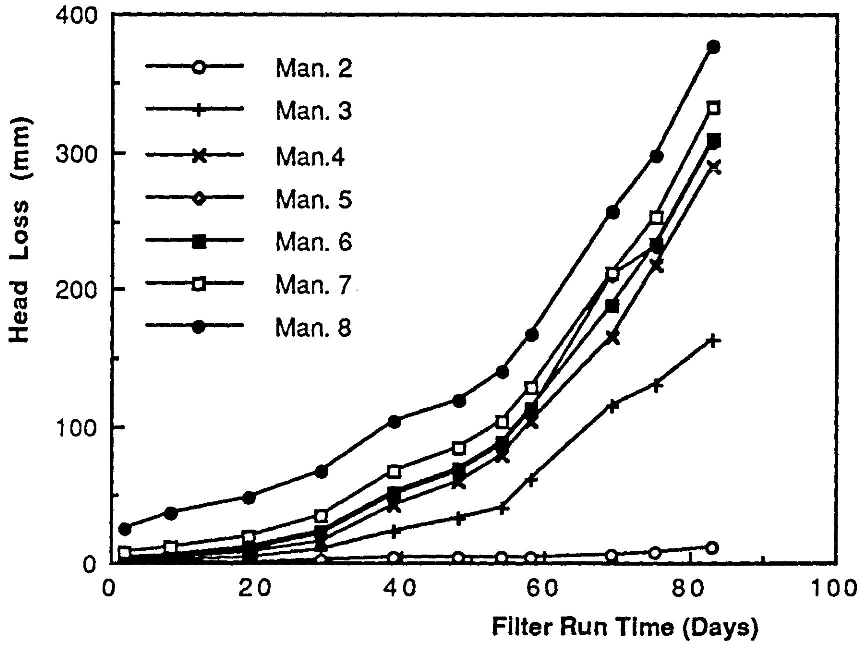


Fig. 5. 2 AFM5 Filter Head Loss (Run 1) ·

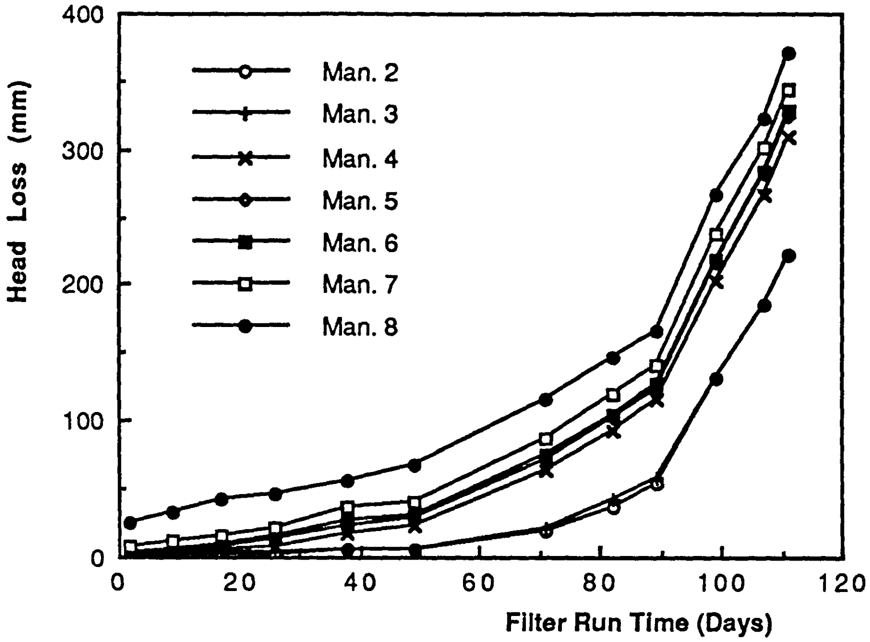


Fig. 5.3 AFM4 Filter Head Loss (Run 1) ·

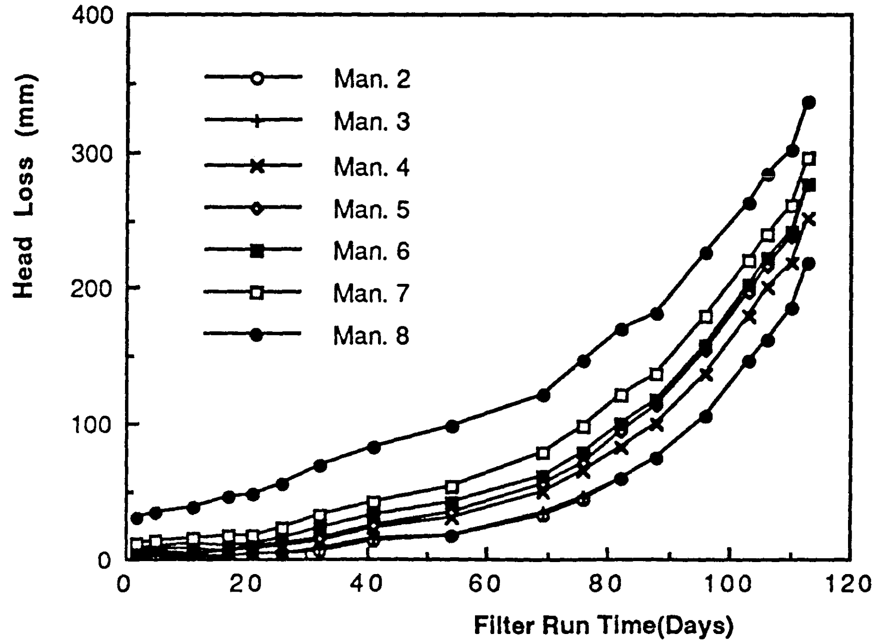


Fig. 5.4 AFM1 Filter Head Loss (Run 1) ·

Although in terms of filter run time there was hardly any real difference between the four and six layer protection, the head loss pattern for the latter depicts a very gradual increase almost until the end of the filter run time. Fig. 5.5 shows the head loss distribution in the unit protected by a single layer lab. No. 32 (AFM2), as expected, penetration of a lot of impurities into the sand bed shows a typical surface filtration in the top sand layer. The NWF lab. No. 32 did not register any readable head loss during this period.

5.5.2 Water Quality Improvements/Changes

5.5.2.1 Water temperature - The maximum water temperature of 11.5 °C in the pilot plant SSF units was recorded in mid - November 1986. The minimum recorded temperature which occurred at the time of the severe winter was 1.7 °C. The overall mean water temperature was 5.93 °C.

5.5.2.2 pH - The inlet water pH varied from 8.0 to 8.3 only thus once again confirming that the source(s) supplied a reasonably stable quality of water. Fig. 5.6 gives the inlet water pH variation from the 22nd day up to the end.

5.5.2.3 Turbidity - Inlet water turbidity ranged from 1.1 to 4.4 NTU. Higher inlet water turbidity was mainly recorded in mid-February 1987 while low turbidities dominated the first few weeks of the field test programme. Table 5.3 gives the mean filtrate turbidity for the six SSF

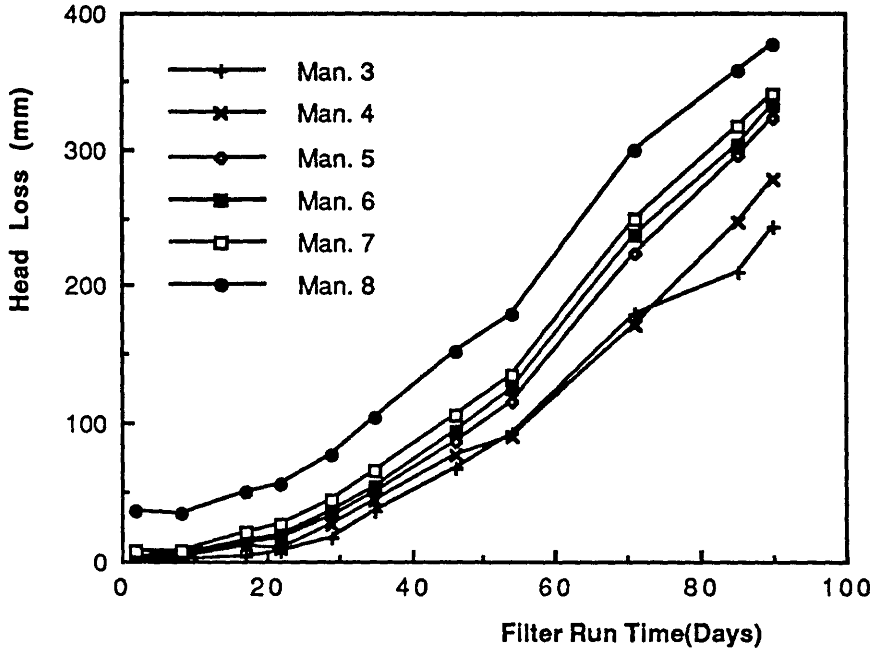


Fig. 5. 5 AFM3 Filter Head Loss (Run 1) ·

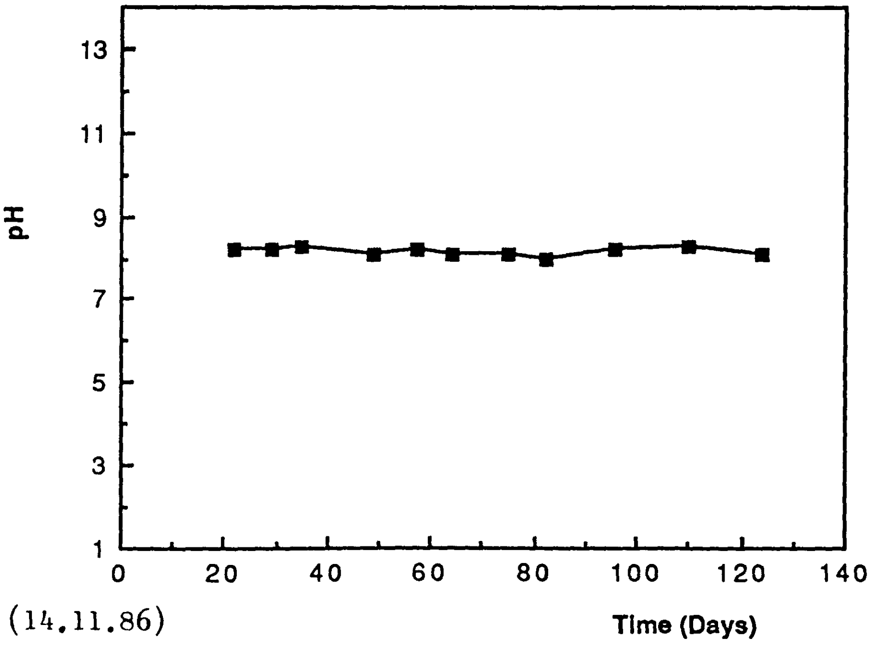


Fig. 5. 6 Inlet Water pH .

units. Except during the maturation period and a few days after cleaning and restarting the SSF units, the mean filtrate turbidity was always less than 0.24 NTU. Fig. 5.7 shows the turbidity removal in the SSF units.

Table 5.3 Mean Filtrate Turbidity

SSF Unit	Mean Filtrate Turbidity	
	NTU	RSD (%)
AFM1	0.21	22
AFM2	0.23	21
AFM3	0.23	20
AFM4	0.21	25
AFM5	0.23	22
AFM6	0.22	23

5.5.2.4 Bacteriological Analysis - This parameter was monitored only from the 3rd December 1986 until the 25th March 1987. Due to severity of the winter season which caused freezing of sampling pipes, no bacteriological samples could be taken between the 7th and 28th January, 1987. The inlet water presumptive Coliforms varied from 118 to 1200 per 100 ml. while the presumptive Faecal Coliforms varied from 38 to 240 per 100 ml. . Tables 5.4 and 5.5 give the raw results of the Coliforms and Faecal Coliforms removals, respectively. In addition, Figs. 5.8 and 5.9 depict the tabulated results graphically. In general, the performance of the SSF units was very good in terms of bacteriological quality improvements. Table 5.6 gives the mean bacteriological removal efficiency of the SSF units. Although the differences are not very

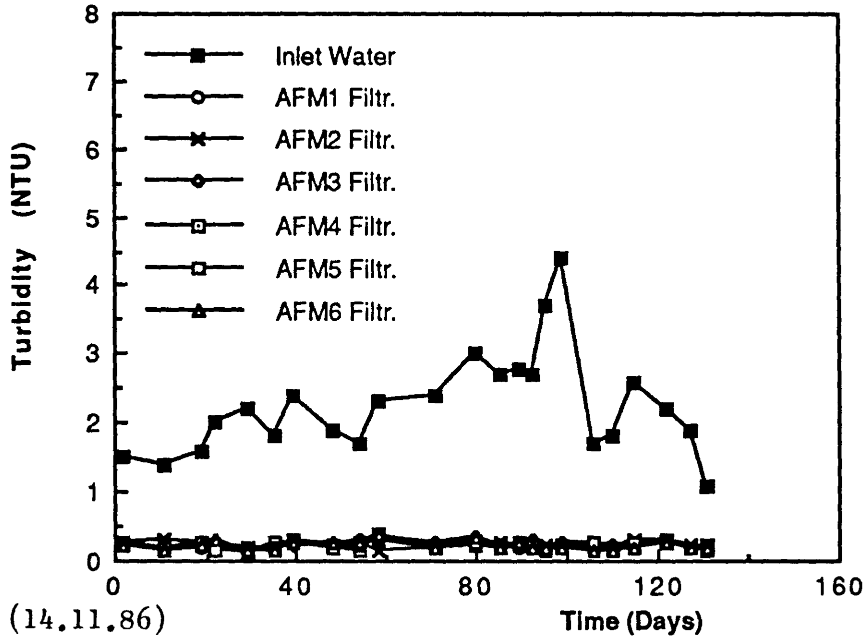


Fig. 5.7 Turbidity Removal in SSF Units ·

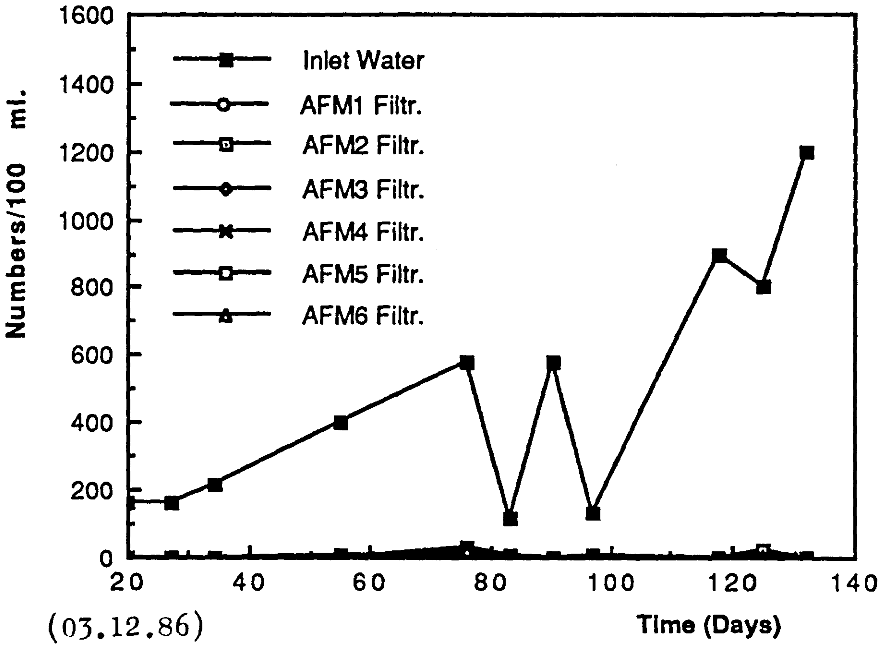


Fig. 5.8 Presumptive Coliforms Removal in SSF Units.

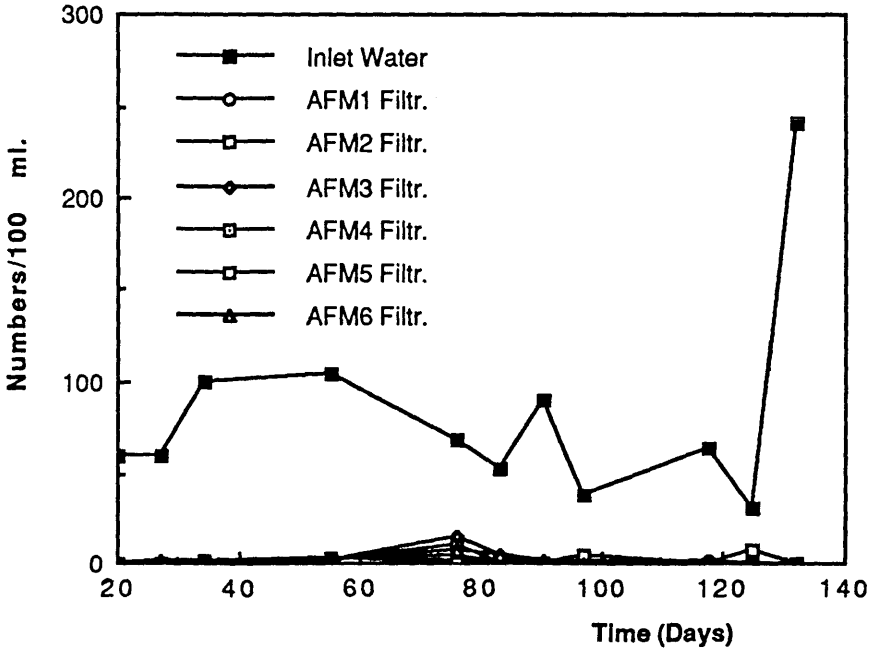
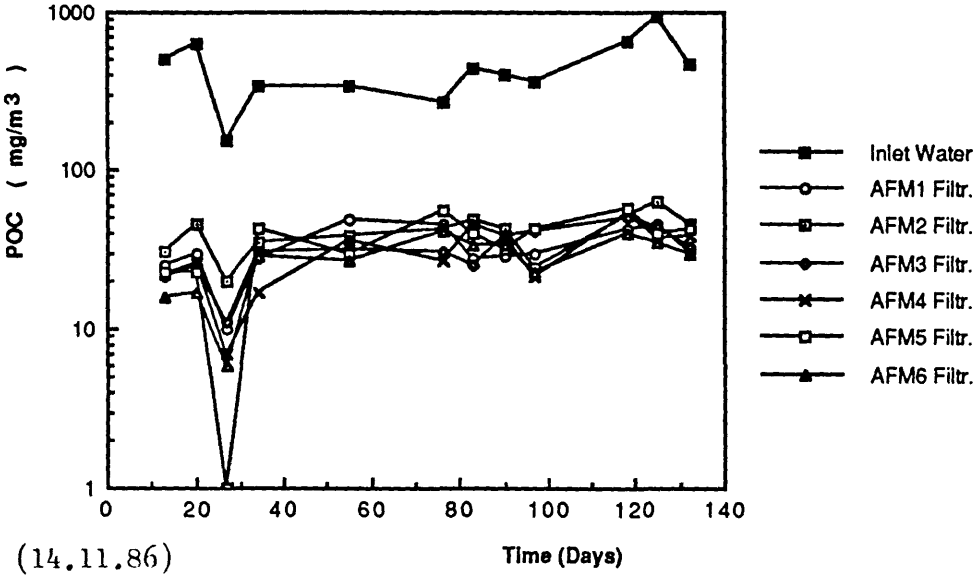


Fig. 5.9 Presumptive E.Coli Removal in the SSF Units.

significant, the units protected by 6 and 4 layers NWF lab. No. 27 represented the best two units. Usually, the filtrate Coliforms never exceeded 4 per 100 ml. .The Faecal Coliforms were usually nil or at most 1. There was a marked decrease in bacteriological quality improvement during the severely cold spell between days number 55 and 83 . Other slightly higher levels were recorded a few days following scraping and re-starting the SSF units.

5.5.2.5 Water POC and Chl-a - These parameters were monitored between the 26/11/86 and 25/03/87. The inlet water POC varied from 151 to 933 mg/m^3 while Chl-a varied from 2.19 to 20.8 mg/m^3. While the mean inlet water POC was 455.3 mg C /m^3 (RSD=45%), the mean Chl-a was 8.94 mg/m^3 (RSD=78%). Table 5.7 gives the mean water POC and Chl-a removal efficiency. Although the differences in performance are not very significant, once again the units protected with 4 and 6 layers of NWF lab. No. 27 were marginally better than the rest. Figs. 5.10 and 5.11 show the POC and Chl-a removal in the SSF units graphically.

5.5.2.6 Particle Size Distribution - This parameter was monitored between 26/11/86 and 18/03/87 with a Coulter Counter model TA II. With exception of AFM2 and the inlet water, the rest of the samples were taken from underneath the fabric mats via a tube connection made to manometer No. 2. The severity of winter prevented sampling during a



(14.11.86)

Fig. 5.10 Water POC Removal in SSF Units.

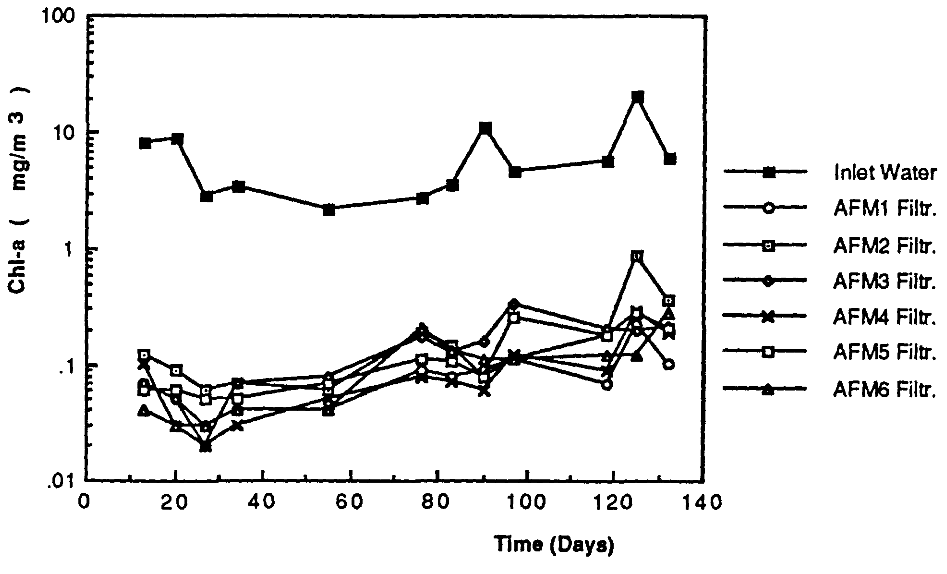


Fig. 5.11 Water Chl-a Removal in SSF Units.

number of occasions due to freezing of the tubes otherwise usually kept running overnight at low rates dictated by isokinetic sampling requirements . In general the overall filtration efficiency of the NWF varied with changes in particle size distribution of the inlet water. The mean number diameter of particles in the inlet water varied from 4.87 to 7.24 μm.

Table 5.4 Presumptive Coliforms

Date	Inlet	Filtrate (No./100 ml.)					
	Water	AFM1	AFM2	AFM3	AFM4	AFM5	AFM6
03/12/86	160	3	1	0	1	0	0
10/12/86	160	0	3	1	0	1	1
17/12/86	220	2	0	1	0	1	2
07/01/87	400	-	2	4	3	4	1
28/01/87	580	8	28	18	8	10	22
04/02/87	118	1	5	8	2	3	7
11/02/87	580	0	0	3	1	2	1
18/02/87	130	0	0	4	0	6	0
11/03/87	900	3	0	0	0	0	0
18/03/87	800	6	20	0	2	1	0
25/03/87	1200	0	2	0	0	0	0

Table 5.5 Presumptive Faecal Coliforms

Date	Inlet	Filtrate (No./100 ml.)					
	Water	AFM1	AFM2	AFM3	AFM4	AFM5	AFM6
03/12/86	60	0	0	0	0	0	0
10/12/86	60	0	0	0	0	0	1
17/12/86	100	0	0	1	0	1	1
07/01/87	104	-	1	2	3	3	1
28/01/87	68	4	10	15	2	0	7
04/02/87	52	0	0	5	2	0	4
11/02/87	90	0	0	0	0	0	1
18/02/87	38	0	0	1	0	4	0
11/03/87	64	1	0	0	0	0	0
18/03/87	30	0	7	0	0	0	0
25/03/87	240	0	0	0	0	0	0

Table 5.6 Mean Bacteriological Removal Efficiency

SSF Unit	Coliform Removal		Faecal Coliform Removal	
	Mean (%)	RSD(%)	Mean (%)	RSD(%)
AFM1	99.3	0.8	99.2	2.2
AFM2	98.5	2.0	98.0	5.3
AFM3	98.1	2.4	95.4	8.1
AFM4	99.4	0.7	98.8	1.7
AFM5	98.6	1.6	98.2	3.7
AFM6	98.5	2.2	97.2	4.0

Table 5.7 POC and Chl-a Removal Efficiency

SSF Units	POC Removal		Chl-a Removal	
	Mean (%)	RSD (%)	Mean (%)	RSD(%)
AFM1	91	4.7	98	0.9
AFM2	90	3.5	97	2.0
AFM3	92	3.1	97	2.5
AFM4	93	3.2	99	1.0
AFM5	91	6.4	98	1.8
AFM6	93	4.1	98	2.2

Table 5.8 gives the mean volume and number removal efficiency for particles in the inlet water. With respect to the number removal, the best protection was afforded by the units with four and six layers NWF lab. No.27 which showed a removal of about 86 % . However, the unit AFM6 with five layers of lab. No. 44 was almost equally efficient with a mean removal efficiency of 85 %. With regard to the mean volume removal efficiency, the three best capture efficiencies were attained by units with four layers lab. No. 27, six layers lab. No. 27 and five layers lab. No. 44 in that order.

Table 5.8 Mean Particle Removal Efficiency

SSF Unit	Number Removal		Volume Removal	
	Mean (%)	RSD(%)	Mean (%)	RSD(%)
AFM1	85.5	12	75.7	17
AFM2	94.7	5	94.8	2
AFM3	64.2	39	48.8	44
AFM4	85.5	12	76.9	18
AFM5	78.7	28	67.9	23
AFM6	85.2	11	75.4	16

5.5.3 Sand POC and Silt Content

The mean characteristics of unused clean sand evaluated on the basis of three samples were:

POC = 0.033 mg C/cm^3 sand (RSD = 46 %)

Silt Content = 0.453 μ g/cm^3 sand (RSD = 30 %)

Table 5.9 gives the results of profile sand sample analysis for POC and silt content taken at the end of the filter runs. An overall review of the tabulated results indicates that the highest specific surface fabric lab. No. 44 offers the best protection to the sand bed. However, the predominance of edge penetration probably soon after blockage of the top fabric allowed deposition of a substantial quantity of silt and POC in the annular area around the NWF edges. Direct comparison of the SSF units with 2, 4 and 6 layers of lab. No. 27 showed that, the double layer was totally inadequate as silt and POC penetration were extensive. The deposits in the sand bed were nearly as high as for the unit provided with the single layer of the NWF lab. No. 32 .

A comparison of the 4 and 6 layers NWF lab. No. 27 showed that better sand bed protection was afforded by the latter. If the results obtained are compared on the basis of equal amounts of water filtered, with regard to POC accumulation in the sand beds, the six layers would allow through less than a third of that which double layer

Table 5.9 SSF Sand Profile POC and Silt Content

SSF Unit	End Filter Run No.	Parameter	Sand Depth (mm)			
			0-25	25-50	50-75	75-100
AFM2	1	POC*	1.82	0.29	0.18	0.13
	2	POC	4.88	0.82	0.40	0.28
	1	Silt**	21.94	2.94	1.67	1.16
	2	Silt	40.92	6.13	2.31	1.56
AFM1	1	POC	0.6	0.40	0.27	0.22
		Silt	4.05	2.47	1.30	0.92
AFM4	1	POC	0.87	0.41	0.24	0.20
		Silt	6.66	2.40	1.32	1.3
AFM5	1	POC	1.42	0.57	0.33	0.24
		Silt	23.49	4.03	2.0	1.22
AFM3	1	POC	1.1	0.47	0.27	0.15
		Silt	16.57	4.24	2.17	1.32
AFM6	1	POC	0.28	0.18	0.14	0.08
		Silt	1.96	1.17	0.94	0.81

* in mg C/cm^3 sand

** in μ g/cm^3 sand

protection of lab. No. 27 can let through. However, under similar circumstances,the four layers would allow through less than half of the amount going through the double layers of NWF lab. No. 27. As regards silt content, while the six layers allowed only about 13 % of the amount allowed by the double layer protection, the four layers allowed only 20 % of the material which went through the double layers of Lab. No.27 .

These observations are once again in conformity with fundamental theories of filtration in view of the dependence of overall capture efficiency on the total depth of the NWF multi-layers. In terms of silt content, the unit provided with a single layer of lab. No. 32 was marginally better protected than the one with two layers of NWF lab. No. 27. In general, all the fabrics provided some protection of the sand beds underneath though with a varying degree of protection. The results of POC and silt content for the reference unit indicate a decreasing amount of accumulation with sand depth during both filter runs completed. However,the data also shows that in lower sand layers(i.e. 25 - 100 mm depth), POC and silt levels increased with time in a manner also observed by Toms et al (122).

5.5.4 Fabrics Cleaning/Washability

In general it was not difficult to clean the NWF with a pressure water hose. However, the cleaning of top fabrics for most of the configurations used took more time than lower layers due to the extensive growth of the biological layer on it. The easiest to clean was NWF lab. No. 32 which was also found to be so delicate that it had to be handled with great care. However, the fact that the NWF lab. No. 32 did not register any head loss at the end of the runs means thorough cleaning was not really necessary. Wheeler et al (81) even suggested recycling of the biological layer formed on/in the fabrics. One factor against the use of fabric lab. No. 32 on its own was the observation of sloughing of deposited materials upon lifting the fabrics. Similar observations have been reported by Rodman et al (82) and Buhl-Nielsen (124).

The washing of the top fabric lab. No. 44 was the most difficult of all since the impurities did not become easily dislodged unless a broom was used to scrub the surface. The colour of the top fabric changed from grey to darkish grey-green while the lower layers became more brownish especially on the edges. Cleaning of the NWF lab. No. 27 was fairly easy and after washing the colour of the top fabric changed from white to light greenish-brown . The bottom layers became a bit brownish especially on the edges. The fabric lab. No. 27 was strong enough to be washed and hosed without changing the physical apprearance of the surface. Both fabrics lab. No. 27 and 44 were found to have good mechanical properties to withstand repeated washing with a pressure water hose and gentle brushing.

5.6 Discussion of Results

On the basis of mean water temperature, the work reported in the preceding chapter was done under warmer conditions (16.7 ^{o}C) than the one reported in this chapter (5.93 ^{o}C). This has major implications with respect to the extent of biological activities taking place in the SSF units. The fact that the mean run time of the reference unit (AFM2) increased from 6 days (reported in the preceding chapter) to 56 days cannot be simply a result of operation at the lower filtration rate. The change in biological activities in the SSF unit must have played a role in increase of the filter run time. However, the main disadvantages of low temperatures is reduction in the capture efficiency of biological related purification mechanisms as demonstrated by the deterioration of bacteriological quality (tables 5.4 and 5.5) during the very cold weather spell in January/February 1987.

On the basis of improvements to filter run time only, both units protected with six and four layers of the NWF lab. No.27 nearly doubled the filter run. However, if due consideration is given to the protection ability of the sand beds as assessed by the penetration of POC and silt also supported by visual evidence of cleanliness of the sand beds, the best protection was afforded by six layers of NWF lab. No. 27 . The configuration with 6 layers can also be expected to have a higher total filtration efficiency than the 4 layers. However, caution must be exercised in making very definite conclusions about the long-term behaviour of the NWF lab. No. 27 on the basis of results of the work reported in this chapter only because only one complete set of filter runs was attained with virgin NWF.

Regarding the fabric lab. No. 44 , so far it has already been proven that it can become completely blinded with time. By the end of the filter run, edge penetration in the unit protected by 5 layers lab. No. 44 was so well established that a 10 cm wide annular ring of heavy silt deposition was noted. This observation seems to tie up with the belief that soon after blockage of the top fabric pores, most of the water was passing around the edges. This phenomenon almost precludes the use of NWF lab. No. 44 on its own for SSF sand bed protection. Although the NWF lab. No. 32 extended the filter run time by a factor of 1.6, its inability to minimize penetration of impurities into the sand bed also rules out its use on its own.

The six layers of NWF lab. No. 27 demonstrated its outstanding ability to reduce the rate of increase of head loss in the fabric protected SSF units (compare Fig. 5.3 & 5.4). This aspect is an additional factor in favour of preference of the six layer lab. No. 27 configuration. With regard to water quality, the differences in overall treatment ability were not very significant but in most cases the performance of the 6 and 4 layer lab. No. 27 fabrics was marginally better than the rest. Particle size distribution analyses done for samples taken underneath the fabrics showed definite distinctions which would otherwise have been obscured by the sand bed if sampled downstream as done in previous experiments. Clearly, the particle number or volume removal efficiency depended on the total filtration efficiency and specific surface of the fabric layers provided.

Table 5.8 shows that lab. No. 32 offered the worst protection followed by 2 layers of lab. No. 27. These results vindicated the decision of taking particle counting samples immediately underneath the NWF layers (s). Note that the range of particle sizes analyzed was only from 4 to 64 μ m equivalent volume diameter. Therefore this study showed that six layers of fabric lab. No. 27 offered the best protection of the sand bed. The sand profile sample POC and silt content analysis indicate a trend of gradual accumulation of POC and silt in deeper layers (25-100mm) of the sand bed in conventional un-protected SSF with time. This observation certainly would justify questioning the wisdom of refilling clean sand in SSF beds immediately after scraping the top layer in the long-term.

Chapter Six

6. THE LONGTERM FILTRATION PERFORMANCE OF THE SELECTED NWF .

These experiments were carried out between 16/09/87 and 19/05/88 at the Ashford Common pilot plant. After qualitatively and quantitatively establishing the potential of the intermediate specific surface NWF lab. No. 27 in protection of SSF beds in the preceding chapter, the experiments reported in this chapter were done for two reasons. The first was to establish the long-term filtration performance of the selected NWF. The other was to quantify the head loss contribution and the treatment performance of a suspended multiple fabric layer of the selected NWF.

Since the fabric lab. No. 27 used during the previous field tests was supplied by special request as an experimental roll of 50 m^2 only, a new order was made for a further 150 m^2 to be used in the field tests reported in this chapter. However, although similar fibres were used for manufacturing the new fabric, SEM analysis showed that the new NWF supplied was needle-felted on multi-filament yarn carrier threads in place of mono-filament yarns (see plates 8 and 9) . This observation together with probable changes in carding settings and/or speed might have resulted in some differences between the new fabric sample (lab. No. 28) and the fabric lab. No. 27. Table 6.1 lists some properties of the two NWF . In general, the differences were very small hence justifying the use of fabric lab. No. 28 in place of No. 27.

Table 6.1 Non-Woven Fabric Properties .

Property	Fabric	
	Lab. No. 27	Lab. No. 28
Fibre diameter(μm)	33	33
Nominal Thickness(mm)	3.6	4.8
Fabric bulk density(g/cc)	0.108	0.100
Porosity (%)	88	89
Specific Surface(m^2/m^3)	14,431	13,266

6.1 Pilot Plant Modifications

The third rehabilitation of the pilot plant was done between May 1987 and 22/06/87, (Clarke, 125) . This involved conversion of two units to support suspended media and replacement of the sand beds in four units. Preliminary experiments done between 23/06/87 and 12/09/87 under the author's supervision are discussed elsewhere (125). The initial design of the suspended layers of filter media presented a number of operational problems suspected to have been caused by excessive sagging of the side supported filter media. These difficulties reinforced the need to change their design in March/April 1988 in order to provide support underneath.

6.2 Reservoir Water Source and Quality

Between June 1987 and May 1988, Ashford Common treatment works received raw water from the Queen Mary and Wraysbury reservoirs. The main source was the Queen Mary but when its quality deteriorated additional water was drawn from one of the Staines group of reservoirs, and in this particular case, Wraysbury reservoir. A survey of weekly identification of algae in the two reservoirs indicated that throughout the experimentation period, Blue green algae and Diatoms were predominant. While the Chlorophyta *Volvox sp.* were dominant only in August and September 1987, other green algae species were predominant as early as June 1987. The yellow green algae *Tribonema* were noticeable from September 1987 until January 1988 and also in May 1988. Some Dinoflagellates were predominant from July until October 1987. Occasional peaks of Cyanophyta (*Anabaena and Aphanizomenon sp.*) and Pennate diatoms were observed. Very high levels of diatomaceous algae were reported in the Queen Mary reservoir in October 1987.

With regard to the identification of the dominant species of animals in the reservoirs, from June until November 1987 and March to May 1988 Cladocerans and Copepods were predominant. However, between December 1987 and February 1988, Cladocerans alone were predominant while Rotifera were observed at high levels in April and May 1988. A high level of *Daphnia sp.* was also reported in June 1988. During this period the maximum reservoir water POC and Chl-a were 2583.2 and 27.55 μg/l, respectively . With regard to the microstrainer filtrate, the maximum POC and Chl-a were 700 and 10.75 μg/l, respectively . Figs. 6.1 and 6.2 show the variation of POC and Chl-a of microstrainer filtrate (inlet to main works SSF) during the experimentation period. It should be noted that during high algal blooms in the reservoirs, the micro-strainers became so much over-loaded that a proportion of the raw water was allowed to go unstrained to the SSF beds in order to maintain the works flow. Fig. 6.3 shows the pilot plant inlet water turbidity variation while Fig. 6.4 shows the bacteriological quality

6.3 Filter Media

The grading curve of sand used as SSF media had an effective diameter (d10) of 0.30 mm and a uniformity coefficient of 1.93, Clarke (125) . Table 6.2 gives the filter media composition of the SSF units during different periods of the experiments. Two different types of filter units were installed; firstly, units AFM1 and AFM5 were provided with equal thicknesses of suspended multi-layer of NWF lab. No. 28 and sand, respectively; the other type comprised four SSF units (AFM2, AFM3, AFM4 and AFM6) of which three were protected with multi-layered NWF configurations listed in table 6.2 . The unit AFM2 was

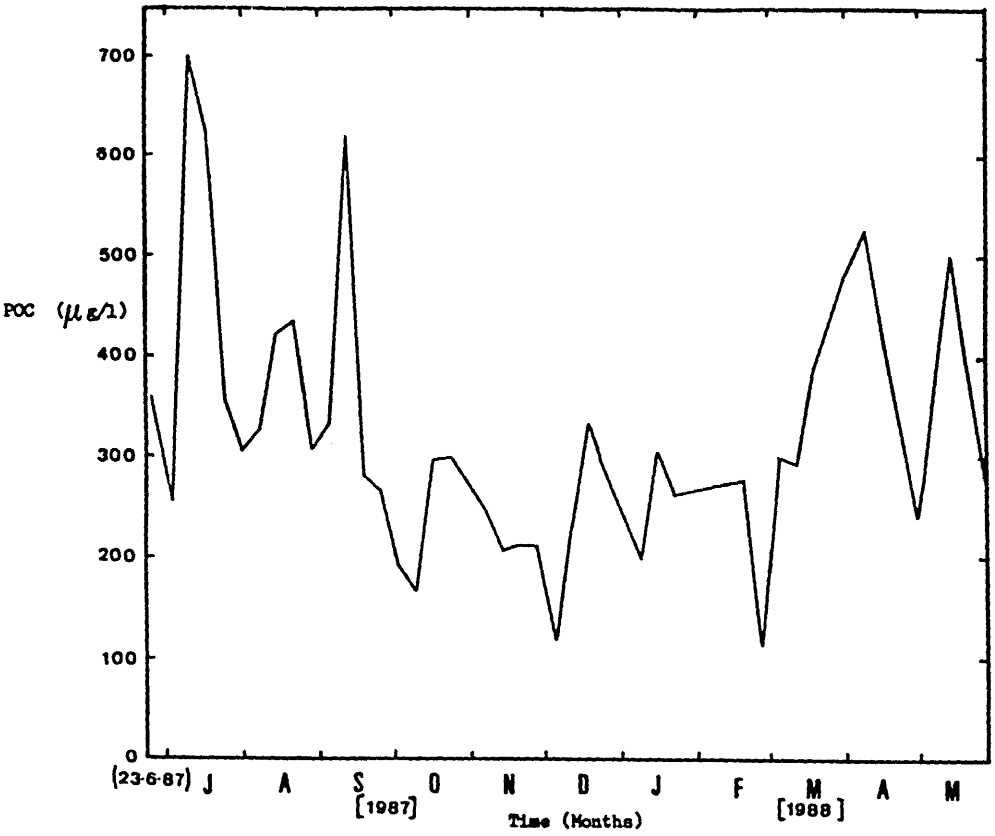


Fig. 6.1 POC Variation of inlet to main works SSF.

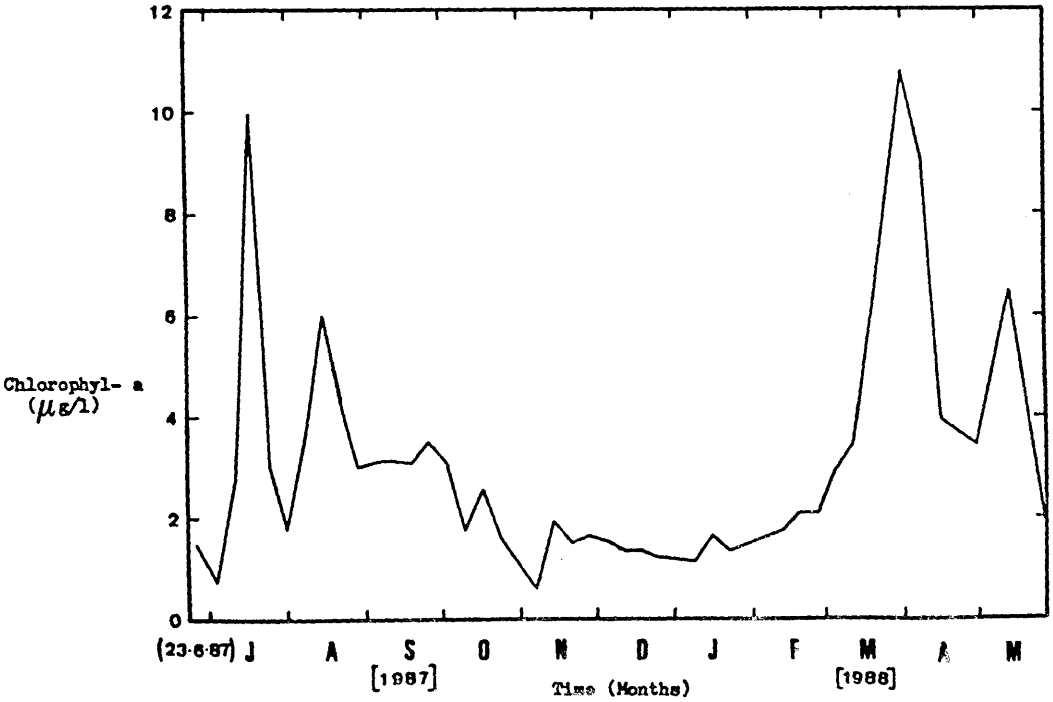


Fig. 6.2 Chlorophyl-a Variation of inlet to main works SSF.

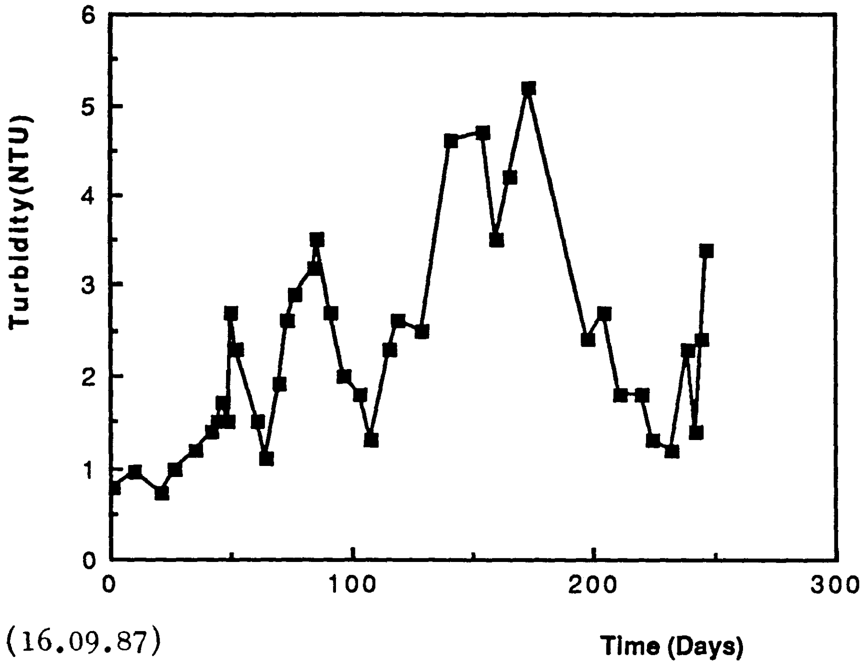


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Fig. 6.3 Inlet Water Turbidity.

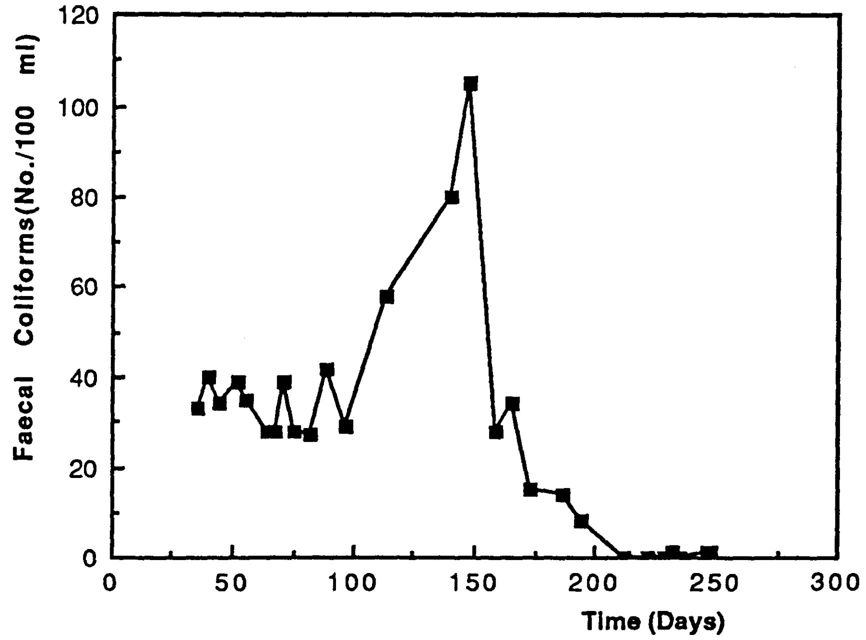


Fig. 6.4 Inlet Water Bacteriological Quality.

used as the main reference SSF and was provided with a conventional unprotected SSF bed depth similar to the other three.

The suspended layer of sand (AFM5) was also provided as a reference for the suspended multi-layer of fabric lab. No. 28 in AFM1 . The new support system for the suspended NWF multi-layer in AFM1 shown on Fig. 6.5 was operational as from the 28/03/88. The sand layer in AFM5 was supported on a 250 micron aperture Nylon mesh (Saatifil-ny, Italy) glued onto a PVC support frame. On 13/04/88, the sand layer was re-supported to appear as shown on Fig. 6.6 .

Table 6.2 Filter Media Composition

SSF Unit	23/06/87-21/12/87 (26 weeks)	22/12/87-17/03/88 (13 weeks)	18/03/88-17/05/88 (9 weeks)
AFM1	5 lab.No.28 only (24 mm thick)	5 lab.No.28 only (24 mm thick)	5 lab.No.28 only (24 mm thick)
AFM2	No Fabric 480 mm sand only (Reference)	No Fabric 480 mm sand only (Reference)	No Fabric 480 mm sand only (Reference)
AFM3	4 lab.No.28 over 1 lab. No.44 (20.5 mm thick) above 480mm sand	No Fabric 480 mm sand only (2nd Reference)	Unit stopped
AFM4	4 lab. No. 28 (19.2 mm thick) above 480mm sand	4 lab. No. 28 (19.2 mm thick) above 480 mm sand	No Fabric 480 mm sand only (2nd Reference)
AFM5	No Fabric 25 mm sand only	No Fabric 25 mm sand only	No Fabric 25 mm sand only
AFM6	6 lab. No. 28 (28.8 mm thick) above 480mm sand	6 lab. No. 28 (28.8 mm thick) above 480mm sand	6 lab. No. 28 (28.8 mm thick) above 480mm sand

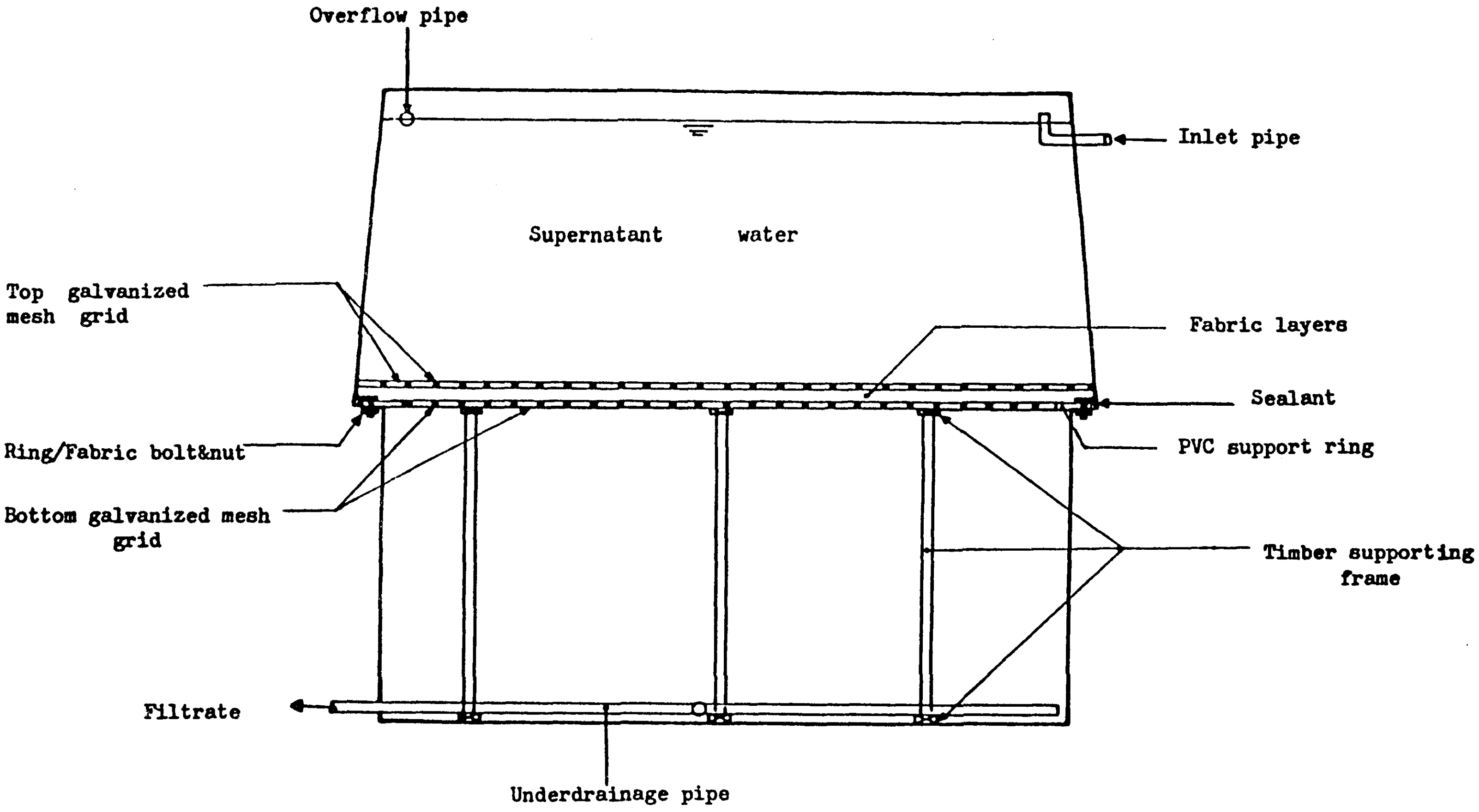


Fig. 6.5 Cross section through the suspended NWF multi-layer unit AFM1.

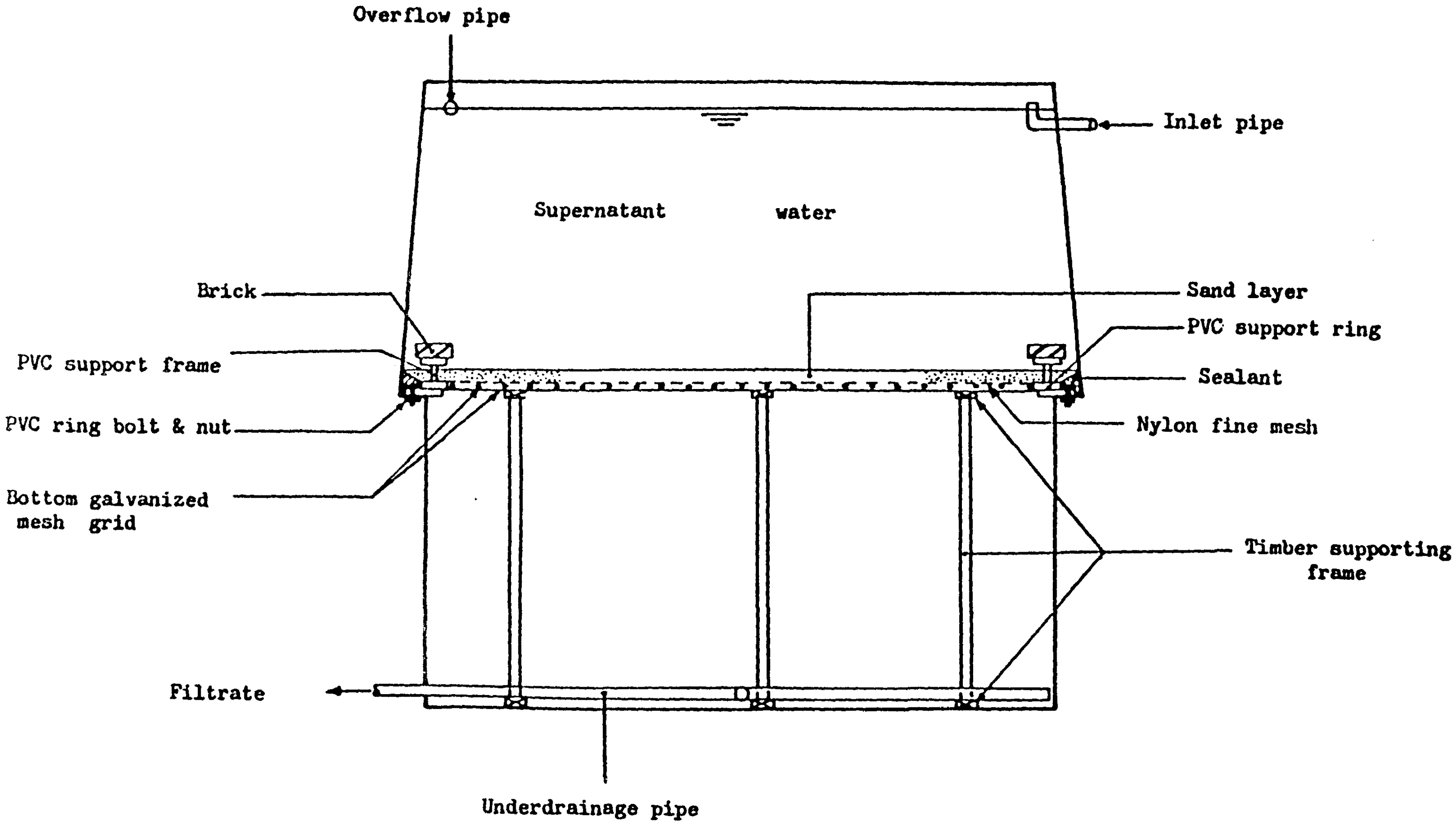


Fig. 6.6 Cross section through the suspended sand unit AFM5.

6.4 General Conduct of Tests

All SSF units were usually operated at a constant filtration rate of 0.15 m/h and filter runs were terminated when this flow velocity could no longer be maintained. Following scraping of sand or cleaning of fabrics, the SSF units were operated at a rate of about 0.10 m/h for four days prior to increasing the rate to 0.15 m/h. To ensure total removal of deposited impurities from the sand bed in AFM2, a depth of about 40 mm of sand was usually skimmed at the end of the filter runs . Usually, new sand was refilled after scraping, however, sometimes no new clean sand could be brought in time for refilling from the washing plant and therefore the unit was re-started without refilling any sand.

From 22/12/87, two reference SSF units with a 480 mm depth of sand only were operated in parallel in order to establish the natural variability in performance of the reference filter. This was also necessary in order to confirm the basis of comparison in chapters four and five. The SSF unit AFM3 had to be stopped on 01/03/88 during its second run as a reference due to excessive leakage around the flow controller base. After effecting the support system changes in AFM1 and AFM5, no further operational problems were experienced. Although the pilot plant was commissioned on the 23/06/87, the reference day (i.e. day number zero) of monitoring the water quality reported in this chapter was on the 16/09/87.

6.4.1 Sampling Frequency and Analysis Methods

During the experiments, temperature, turbidity, faecal coliforms, particle size distribution and filter head loss were analyzed/measured on a daily basis while faecal coliforms enumeration was done at least once per week. Inlet and filtrate water samples were taken for turbidity and faecal coliforms enumeration. As regards the methods of analysis, with exception of faecal coliforms, the other parameters were measured according to the techniques described in chapter four (section 4.2) . Faecal Coliforms enumeration was done by the membrane filtration technique using the "Delagua" field water testing kit (University of Surrey, Guildford, UK). Duplicate tests of membranes were analyzed for each sample tested. The averages of the duplicates were reported as the results in numbers/100 ml. The experimental procedure followed is given in detail elsewhere (126).

6.5 Discussion of Results

The results are discussed in three separate sections; these are hydraulic performance, water quality improvements/changes and impurities deposition pattern.

6.5.1 Hydraulic Performance

6.5.1.1 Filter Run Time - Table 6.3 gives the filter run times for the reference and the fabric protected SSF units. The average filter run time of 38 days for the main reference filter (AFM2) compared well with the main works SSF units. The successive AFM2 filter runs completed are indicated in brackets in table 6.3 .

Table 6.3 Filter Run Times

SSF Unit	Filter Media Composition	Average Filter Run Time (Days)	Extension Factor
AFM2	Sand only (Reference)	38 (25,37,37,32,51,48)	-
AFM3	4 lab.No. 28 over 1 lab. No. 44	160*	4.2
AFM4	4 lab. No. 28	178*	4.7
AFM5	25 mm sand	32*	0.84
AFM6	6 lab. No. 28	319*	8.4

* Single filter run

In order to separate and quantify actual differences in filter run times because of the application of NWF from natural variations between two parallel units, two main reference filters were operational for certain periods of the investigation (see table 6.2) . The average run time for AFM4 as a reference unit was 40 days which compared well with AFM2. The AFM2 winter run time of 51 days was also fairly comparable to 56 days recorded for AFM3 as a reference just a month later. On the basis of this evidence it was concluded that there were no significant behavioural differences in the sand media of AFM2, 3, 4 and AFM6 . This was therefore assumed to be also true for the test results given in chapters four and five.

The magnitude of improvement to the filter run time by the application of NWF layers is shown in table 6.3 . Unfortunately, as a result of the very long run times of AFM3, 4 and 6 it was not possible to achieve successive filter runs after the first. It therefore still remains as an uncertainty what the long-term average run times would have been for these units under the operational conditions studied at Ashford common. However, Evidence from parallel studies done at Egham with fabric lab. No. 28 showed that the average filter run time would not be expected to decrease with time as long as the fabric is washed properly at the end of the filter runs.

6.5.1.2 Filter Head Loss - Because of the advantageous properties of NWF, the consequential head loss development in fabric multi-layers is much slower than for the reference filters (s). This is for example evident from the head loss data for units AFM1 and AFM5 where the latter (25 mm sand layer) reached its operational limit after only 32 days (see Fig.6.7) in contrast to a similar thickness of NWF lab. No. 28 which registered a head loss of only 10 mm

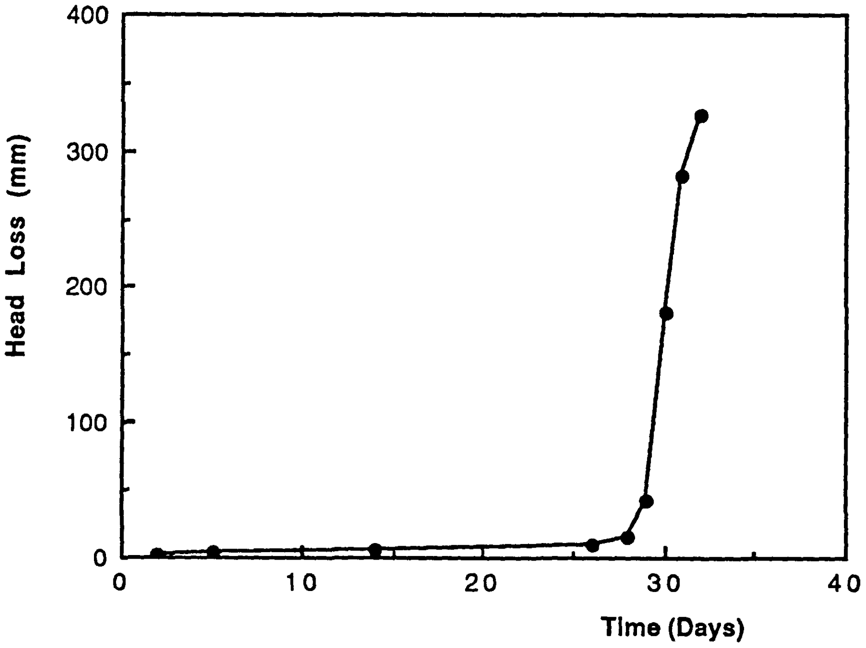


Fig. 6.7 AFM5 Filter Head Loss (Last Run).

after 50 days. Note the sudden rise of the head loss of the thin sand layer beyond the 28th day. Figs. 6.8 and 6.9 give some head loss profiles of the reference unit AFM2 which typifies surface filtration. In Fig.6.8, the exponential increase in the head loss starts as early as the 10th day while in Fig. 6.9 the same starts after the 13th day. However, in the latter case, a brief head loss recovery persists between the 24th and 30th days of the filter run. These recoveries were observed during most of the filter runs of the SSF units regardless of whether they were fabric protected or not.

Fig. 6.10 shows the head loss profile in the unit AFM4 provided with 4 layers lab. No. 28 . The profile shows a considerable delay in the exponential rise of head loss which started beyond the 115th day of the run. The head loss profile shows a fairly substantial contribution of manometer tube No. 2 in head loss besides the evident penetration of impurities on the sand bed observed at the end of the run. Note the mini-recovery which appears on the graph . Fig. 6.11 shows the head loss profile in the unit protected with six layers of lab. No. 28 . The delay in occurence of the exponential increase of head loss was about 120 days which is fairly similar to Fig. 6.10 . The head loss increased up to the 250th day beyond which a recovery and one brief steep rise occurred before the head loss continued to fall in all manometer tubes. It is not

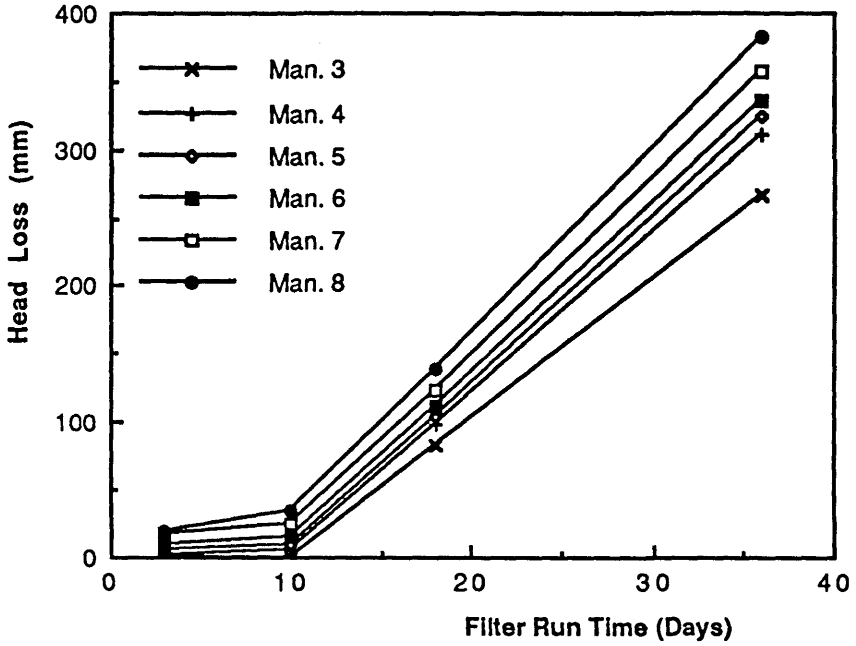


Fig. 6.8 AFM2 Filter Head Loss (Run 1).

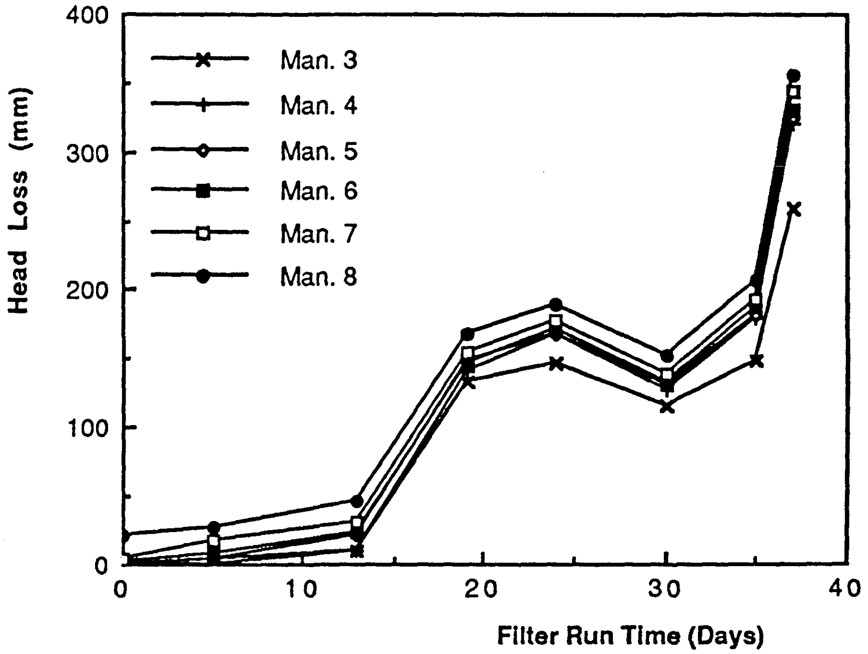


Fig. 6.9 AFM2 Filter Head Loss (Run3).

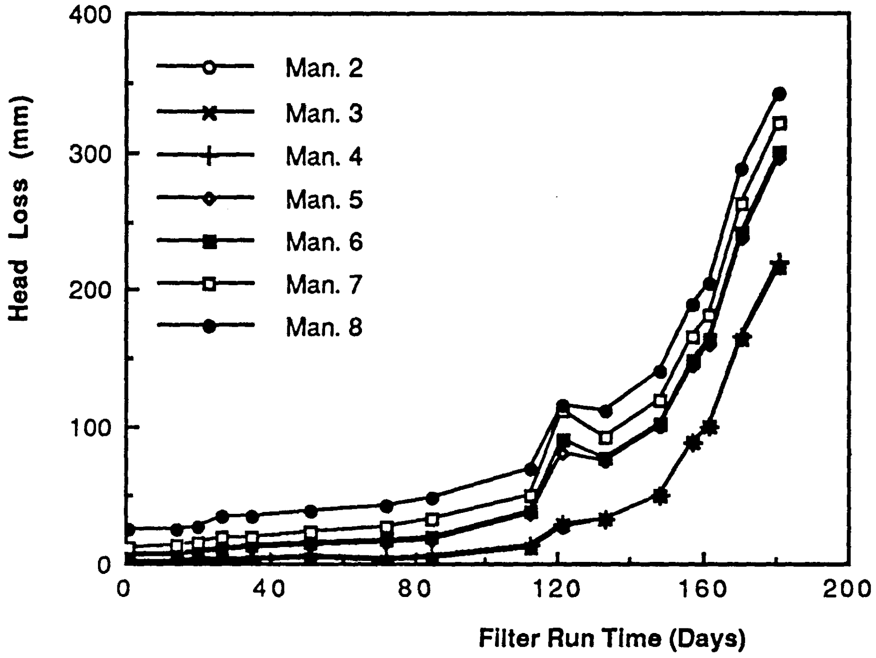


Fig. 6.10 AFM4 Filter Head Loss (Run 1).

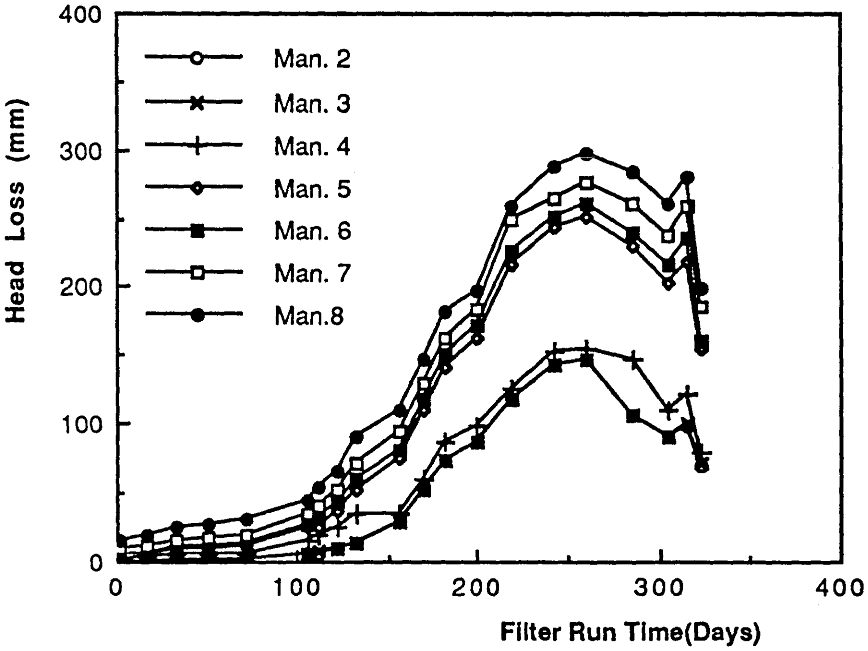


Fig. 6.11 AFM6 Filter Head Loss (Run 1).

very clear why the head loss decreased towards the end of the filter run.

Since at the end of the filter run time the filter bed appeared to have been so well protected that visually one could not tell the difference between it and clean unused sand, it is not easy to account for the gap between the manometer tubes No. 4 and 5 in AFM6 which persisted immediately after the begining of the steep increase in head loss. Excavation of the sand layer over a depth of about 300 mm showed no evidence of deposits in the sand bed or on the manometer tubes tapping points which were covered with stainless steel meshs. The only unusual observation in the unit AFM6 was the fact that manometer tube No. 4 used to release a lot of gas bubbles when drained as a result of registering unusually low readings. However, the fact that this SSF unit was continuously operational for a total of 46 weeks makes it difficult to predict with confidence the biological factors which might have been responsible for the head loss profile observed (if any).

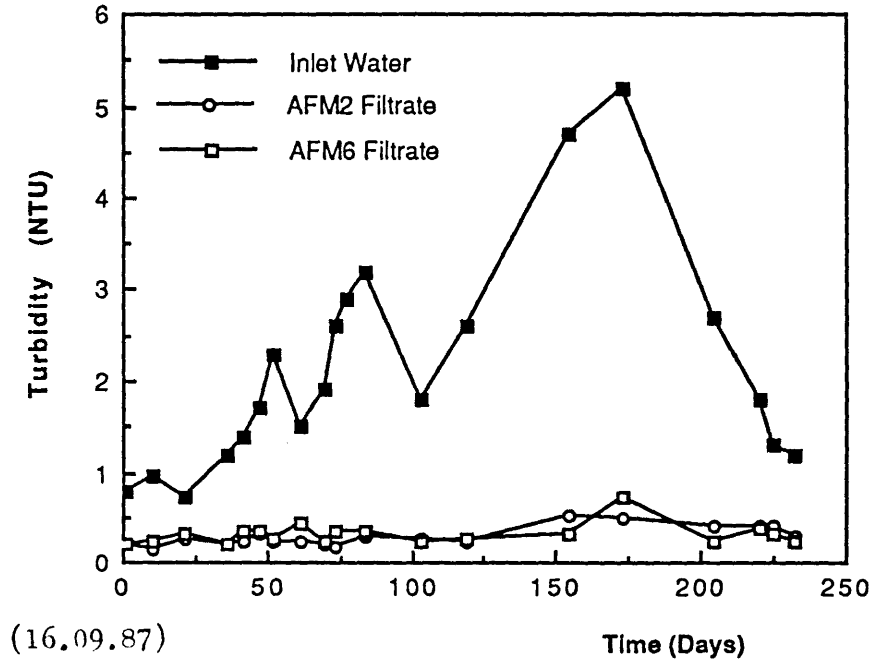
6.5.2 Water Quality Improvement/Changes

6.5.2.1 Temperature - From 16/09/87 until 19/05/88, the ambient air temperature ranged from 3.0 to 21.0 ^{o}C and the SSF supernatant water temperature ranged from 3.5 to 17.8 ^{o}C . During the field test programme, the mean water temperature was 8.6 ^{o}C.

6.5.2.2 Turbidity - Between 16/09/87 and 19/05/88, the inlet water turbidity ranged from 0.95 to 5.2 NTU . During this period, the performance of the SSF units AFM2, 3, 4 and 6 with respect to turbidity showed no significant differences regardless of whether they were fabric protected or not. The filtrate turbidity of these units ranged from 0.20 to 0.45 NTU . Fig. 6.12 shows the turbidity improvement in the main reference and the unit protected with six layers of lab. No. 28 during the period under mention.

For the suspended media units AFM1 and AFM5, a good comparison of their performance was only possible during the period between 13/04/88 and 19/05/88 after re-supporting them . During this period, average filtrate turbidities of 0.55 and 0.66 NTU were observed for AFM1 and AFM5, respectively . This would suggest a slightly better performance of the suspended fabric multi-layer than sand. However, it should be kept in mind that the unit AFM1 was re-started two weeks earlier than AFM5.

6.5.2.3 Bacteriological Quality - Between 21/10/87 and 19/05/88, the influent water Faecal Coliform counts ranged from 0 to 105 per 100 ml. . There were no Faecal Coliforms detected during the whole month of April 1988. This phenomenon might have been caused by changes in the ecological regime in the main works SSF supernatant water as a result of the spring algal blooms along with the high levels of Rotifera, acknowledged as bacterial predators



(16.09.87)

Fig. 6.12 Turbidity Removal in SSF Units.

Table 6.4 Faecal Coliforms per 100 ml.

		SSF Unit					
Date	Inlet Water	AFM1	AFM2	AFM3	AFM4	AFM5	AFM6
21.10.87	33	1	0	1	0	-	0
25.10.87	40	1	0	0	0	-	0
30.10.87	34	2	0	1	0	-	0
06.11.87	39	2	0	2	0	24	1
10.11.87	35	2	0	0	0	21	0
18.11.87	28	2	0	1	0	16	1
22.11.87	28	3	1	1	0	27	1
25.11.87	39	3	1	0	0	32	1
29.11.87	28	2	1	1	1	30	1
06.12.87	27	3	0	2	1	27	1
13.12.87	42	3	0	-	0	38	2
21.12.87	29	4	1	5	0	-	0
06.01.88	58	39	0	-	0	-	0
02.02.88	80	48	-	0	-	-	-
10.02.88	105	63	-	0	-	-	0
21.02.88	28	7	1	1	2	7	0
28.02.88	34	10	0	3	0	5	0
06.03.88	15	14	0	-	0	7	0
20.03.88	14	-	0	-	1	-	0
27.03.88	8	-	-	-	0	0	0
14.04.88	0	0	0	-	0	0	0
24.04.88	0	0	0	-	0	0	0
01.05.88	0	0	0	-	0	0	0
04.05.88	1	0	0	-	0	1	0
08.05.88	0	0	0	-	0	0	0
19.05.88	1	0	0	-	0	0	0

(38,85) which were observed in the raw water reservoirs in April and May 1988. Table 6.4 gives a summary of the Faecal Coliform concentrations determined during the study period. In general, SSF units AFM2, 3, 4 and 6 showed very satisfactory removals (>95%) all the time such that if filtrate counts were not nil then they were in most cases not more than 2 per 100 ml. . The latter counts usually occurred a few days after cleaning the units or after some form of flow disturbance. However, the results for the suspended layer fabrics (AFM1) and sand (AFM5) showed higher filtrate Faecal Coliforms during periods of operational problems like pumps or power failure and in both cases, after rehabilitation no Faecal Coliforms were detected in the filtrate. Table 6.5 gives the bacteriological removal efficiency of four SSF units which were composed of either sand alone or fabric protected sand. The periods of comparison are only up to the time when either the units were changed/shut down (AFM4 & AFM3) or at the end of their last run in May 1988 (AFM2 & AFM6).

Table 6.5 Faecal Coliform Removal Efficiency

Unit	Faecal Coliform Removal Mean (%)	 Minimum (%)	RSD (%)
AFM2	99.1	96.4	2.1
AFM3	97.1	92.6	3.4
AFM4	99.2	94.6	2.5
AFM6	98.9	95.2	2.4

6.5.3 Impurities Deposition Pattern

For unit AFM3 with 4 layers lab. No. 28 impurities appeared to have penetrated fully into the top three layers with intense biological activities confined to the top two fabric layers. Partial penetration of the fourth layer and also into the bottom fabric was observed. In this case it seems the blockage of pores in the bottom fabric (No.44) might have been responsible for bringing about an earlier end of the filter run time. Penetration of a few impurities through to the sand bed was visible and edge penetration was very apparent on the sand bed upon removal of the fabrics. After establishing the unsuitability of fabric lab. No. 44 for sole filter protection in the preceding chapter, this observation rules out the use of calendered NWF for protection of SSF sand beds. It can be recalled that in chapter four, the permeability of used and washed NWF lab. No. 44 was found to have progressively decreased with time . The unit AFM4 with four layers of lab No. 28 showed a deposition pattern somewhat similar to AFM3 but in this case visible impurities which penetrated into the sand bed were more established and deeper (about 20 mm); edge penetration was apparent though to a much lesser extent than in AFM3 . This suggests that the thickness of the fabrics provided was not quite sufficient, as suspected in chapter five. Unfortunately no sand profile POC or silt content analyses were possible.

In the case of AFM6 with six layers of the NWF lab. No. 28, inspection of sand throughout the bed depth at the end of the filter run showed no visual evidence of solids accumulation or impurity deposition. After draining the supernatant water of AFM6 at the end of the filter run, a large quantity of micro-organisms were observed to be grazing in the filamentous algae weeds which were attached to the mesh grid and also onto the fabric fibres. This attachment of algae prevented them from floating during the day and hence causing operational problems related to disturbance of the schmutzdecke which have been previously reported in conventional SSF units (11,54). The algae layer was full of silt thus indicating that it acted as an additional filter medium. This might help to give partial explanation of the very high filter run extension factor of AFM6 in comparison to say AFM4 .

In agreement with the observations of other workers (54), Trichoptera, May flies (Ephemeroptera), Midges (Chironomids) and some crustaceans (Daphnia, Bosmina) were identified on the schmutzdecke. Impurities penetrated extensively through the top two layers of fabrics. The middle two fabric layers showed considerable silt deposition but not as much as the top two layers. The bottom fabrics were lightly tainted brown as a result of some edge penetration.

Chapter Seven

7. THE USE OF NWF TO PROTECT SSF TREATING CHEMICALLY PRETREATED WATER .

This study was carried out between April 1987 and May 1988 with a pilot plant located within the premises of the North Surrey Water Company, Staines, Surrey. The main objective of this study was to quantify and optimize the benefits of protecting SSF with NWF when treating coagulated river water which has substantial flocs carry-over and to compare the effectiveness of several types and/or configurations of NWF. In drinking water treatment, coagulation is usually applied when treating raw water sources with significant turbidity and/or colour. Although the use of SSF downstream of coagulation is not a typical drinking water treatment process configuration, a number of rural water supply plants have been provided with this water treatment system in Tanzania (39,40). In theory, such a treatment scheme is supposed to be appropriate. However, in practice sometimes operational difficulties with pre-treatment units result in overloading the subsequent SSF with flocs carry - over. Therefore, one of the aims of carrying out the study reported in this chapter was to assess whether or not NWF can be successfully applied to substantially extend the filter run times of the SSF units operated under such circumstances.

7.1 Pilot Plant Description

7.1.1 Pilot Plant Design

The SSF units were designed to be operated at a filtration rate of 0.15 m/h with provision for operation at a maximum rate of 0.30 m/h. Three rectangular SSF units, each with a length, width and depth (internal dimensions) of 1.8 m, 1.2 m and 1.6 m, respectively, were designed. Each unit was provided with a 200 mm thick underdrainage system and a 600 mm depth of sand bed. A supernatant water depth of 750 mm and a free board height of 50 mm were provided. Fig. 7.1 shows a typical cross section through a SSF unit. Six manometer tubes used for filter head loss measurement were located at 50 mm above the sand bed (No.1), at the top level of sand (No.2) and then successively at 50 mm (No.3), 200 mm (No.4), 500 mm (No.5) and 700 mm (No.6) below the top level of sand, respectively. Two upflow sludge blanket clarifiers each with a diameter of 1.0 metres (see Fig.7.2) designed and manufactured as described by Hunter (127) were used for pre-treatment of river Thames water. Since it was necessary to ensure a continuous supply of pretreated water, the clarifiers were designed to be operated either in series or separately. The clarifiers were fed by an overhead mixing tank in which river water was mixed thoroughly with Poly-Aluminium Chloride (PAC) downstream of a $60^{o}C$ vee-notch weir. The mixing tank and the weir were designed in accordance with BS:3680:1981, Part 4A (128).

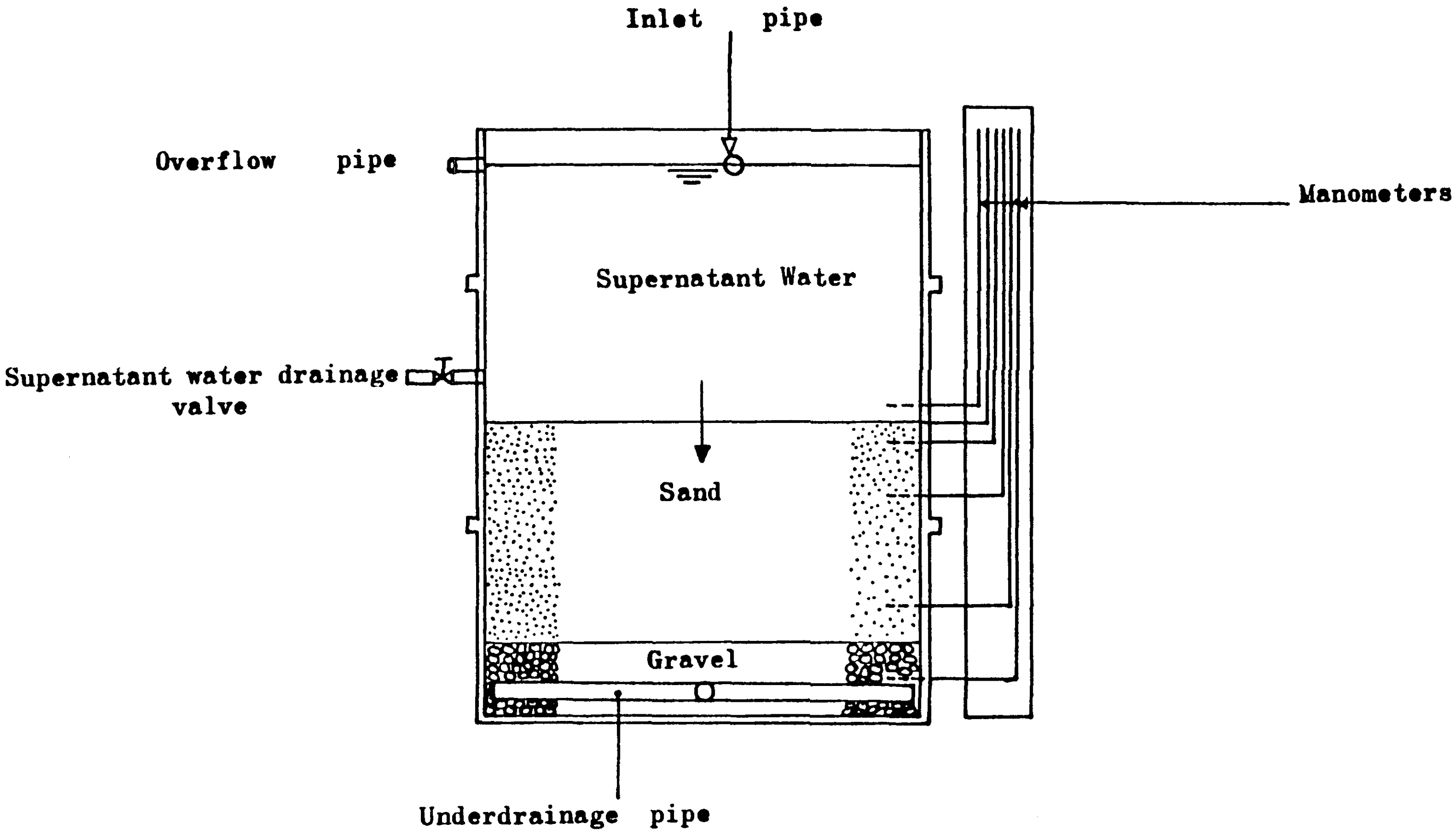


Fig. 7.1 A Typical Cross Section of a SSF Unit. (Not to Scale)

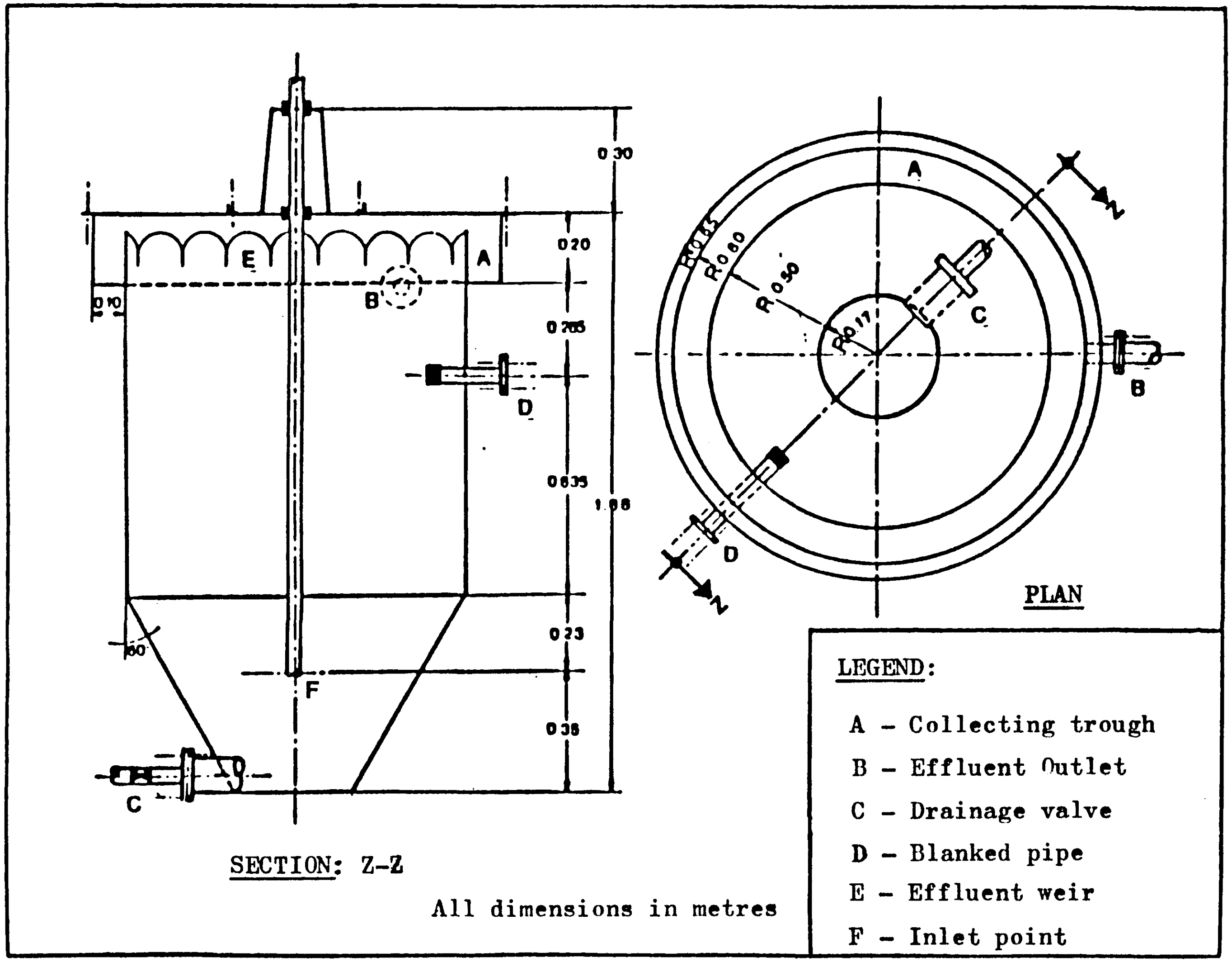


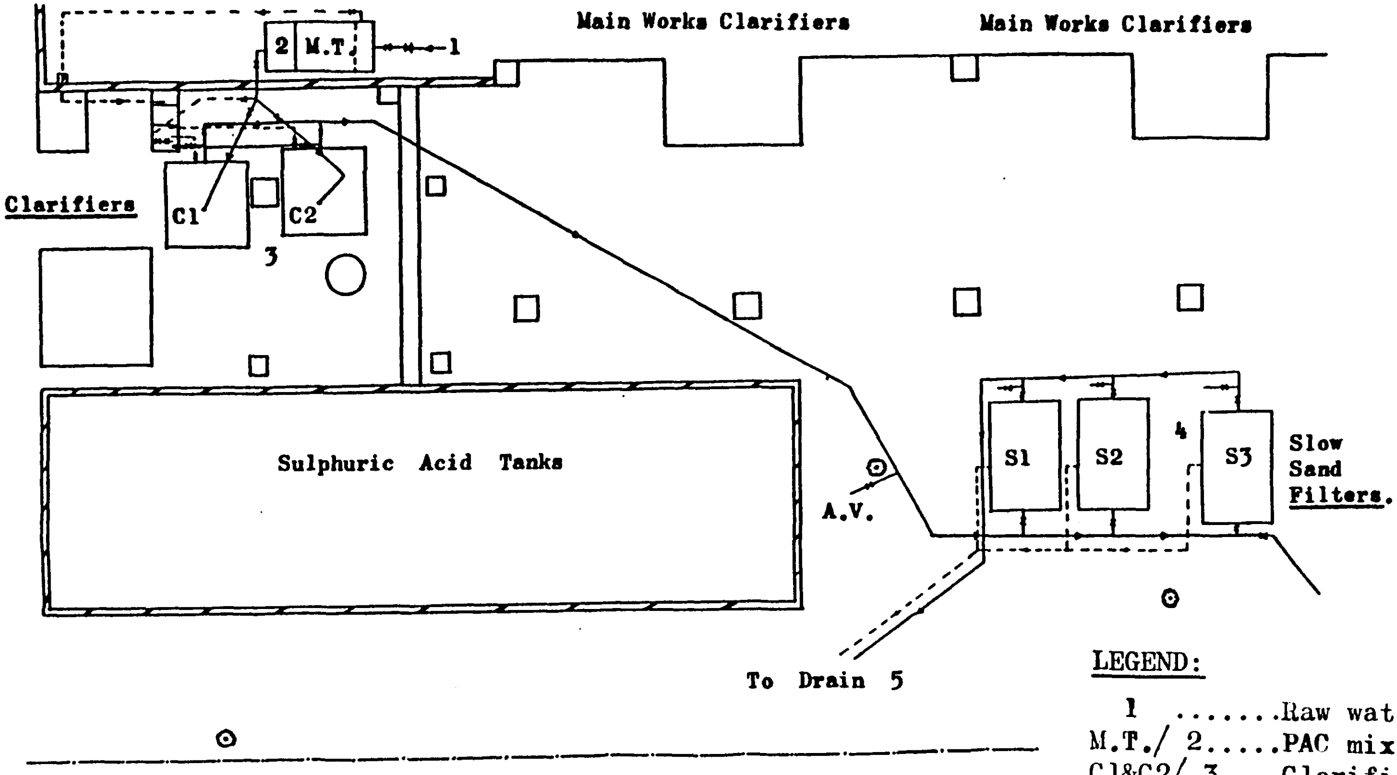
Fig. 7.2 Plan and Cross section of the clarifier (Modified after Hunter, 1986, (127)).

7.1.2 Installation and Time Schedule

The manufacture , initial modification of the clarifiers and installation of the SSF units was done between May and July 1987. Preliminary experiments carried out in August/September 1987 (129) under the author's supervision led to changes in the raw water extraction system and the chemical dosing facilities. At the end of November 1987, the clarifiers were commissioned and after completion of the modifications, the pilot plant pipe system was insulated with an 105 mm thick fibre glass loft insulation (Supawrap, Pilkington, UK) . The conduct of experiments was divided into two main phases. Phase 1 covered the period between 30/11/87 and 07/03/88 while phase 2 covered the period between 08/03/88 and 07/05/88 .

7.1.3 Pilot Plant Flow Sheet

While the pilot plant layout is shown on Fig. 7.3 , the schematic hydraulic profile is shown on Fig. 7.4. At the start of the process line an MF/VO - 502 W/ks vortex impeller submersible pump (Hodson Croydon Ltd.) drew raw water from river Thames at the main works intake and delivered it into the PVC chemical mixing tank (located on the roof of the chemical house) via a 40 mm diameter pipe. Optimal pH conditions were achieved by drawing the raw water downstream of the main works pH correction system. In



LEGEND:

1 ......Raw water inlet
M.T./ 2.....PAC mixing tank
C1&C2/ 3 ...Clarifiers
S1-S3/ 4 ...Slow sand filters
5 ....Drainage pipe
—·—· ......Fence
✿ ......Tree
—▷◁— ......Gate valve

Fig. 7.3 Egham Pilot Plant Layout Plan (Approximately to scale).

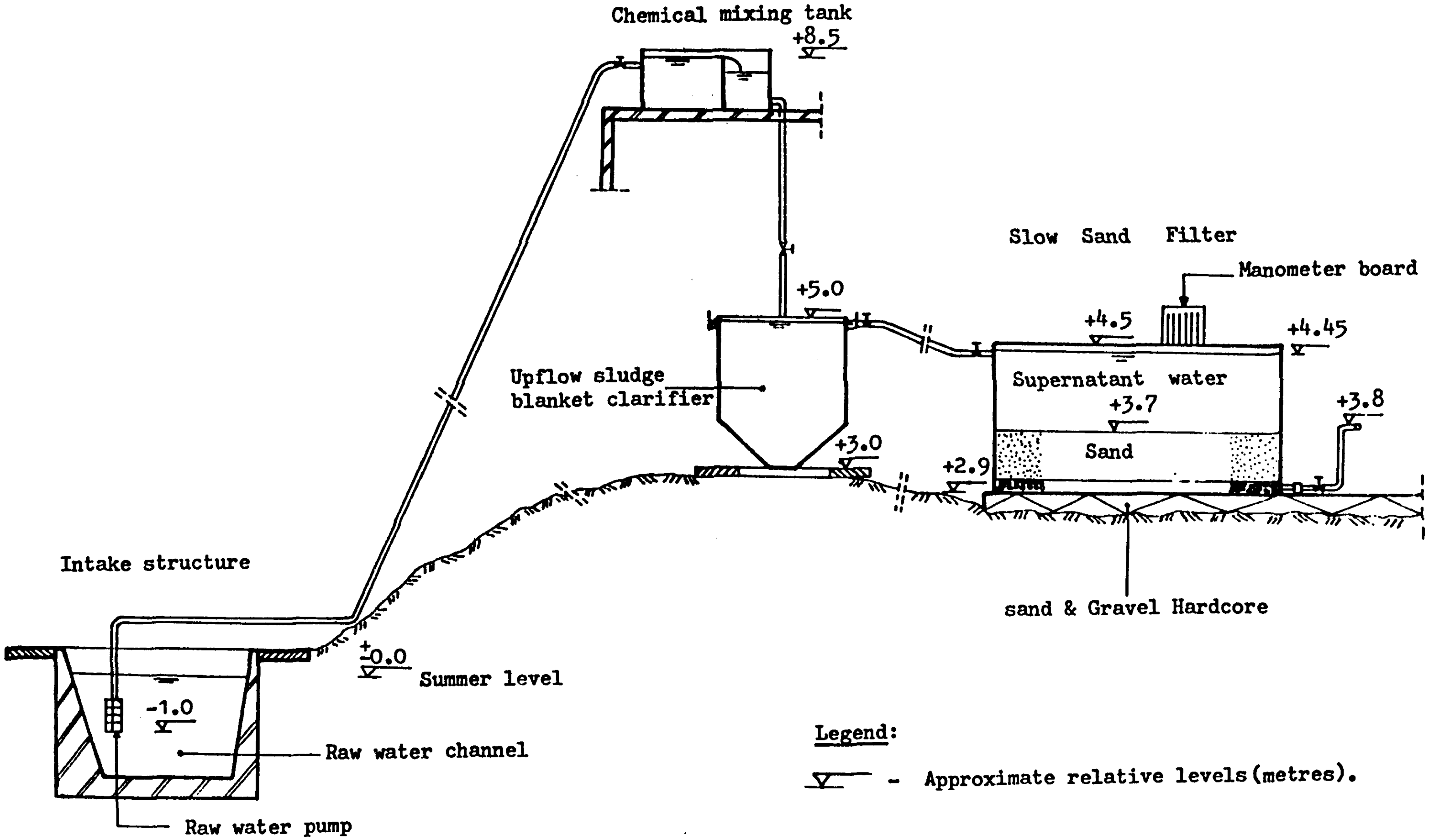


Fig. 7.4 Schematic hydraulic profile of Egham pilot plant.

the mixing tank Poly-Aluminium Chloride (Laporte Ind. Ltd., UK) was added downstream of the vee-notch weir in correct proportion in order to coagulate impurities (colour and turbidity) in the raw water. The PAC storage container located next to the mixing tank (see plate. 20) was provided with a model BD 6931 (BDH, UK), 300 W electro-thermal red rod immersion heater (connected to an MC-225 power regulator) to keep the PAC solution (10% strength weight/weight as Al_2O_3) within a temperature range of 10 to 20 ^{o}C . PAC was dosed into the mixing tank with the help of a model 60-128 WAB peristaltic tube-pump (Glen Creston, Middlesex) connected to a dosing beaker and one recirculation line.

From the mixing tank, coagulated water flowed through a 3.0 metres long, 40 mm diameter vertical pipe in which further intense mixing took place. Then it was led into two upflow sludge blanket clarifiers operated under uniform conditions ensuring carry-over of flocs into the subsequent unit operation by adjustment of the top blanket level at a very high location relative to the settled water extraction level. The combined clarifiers effluent was then led into three SSF units (see plate.21) provided with varying media composition in order to compare the hydraulic and treatment performance. The walls of SSF boxes manufactured by Instalrite plastics ltd., Windsor, were composed of an inner PVC lining covered with a reinforced glass fibre layer strengthened by two metal girders over the height.

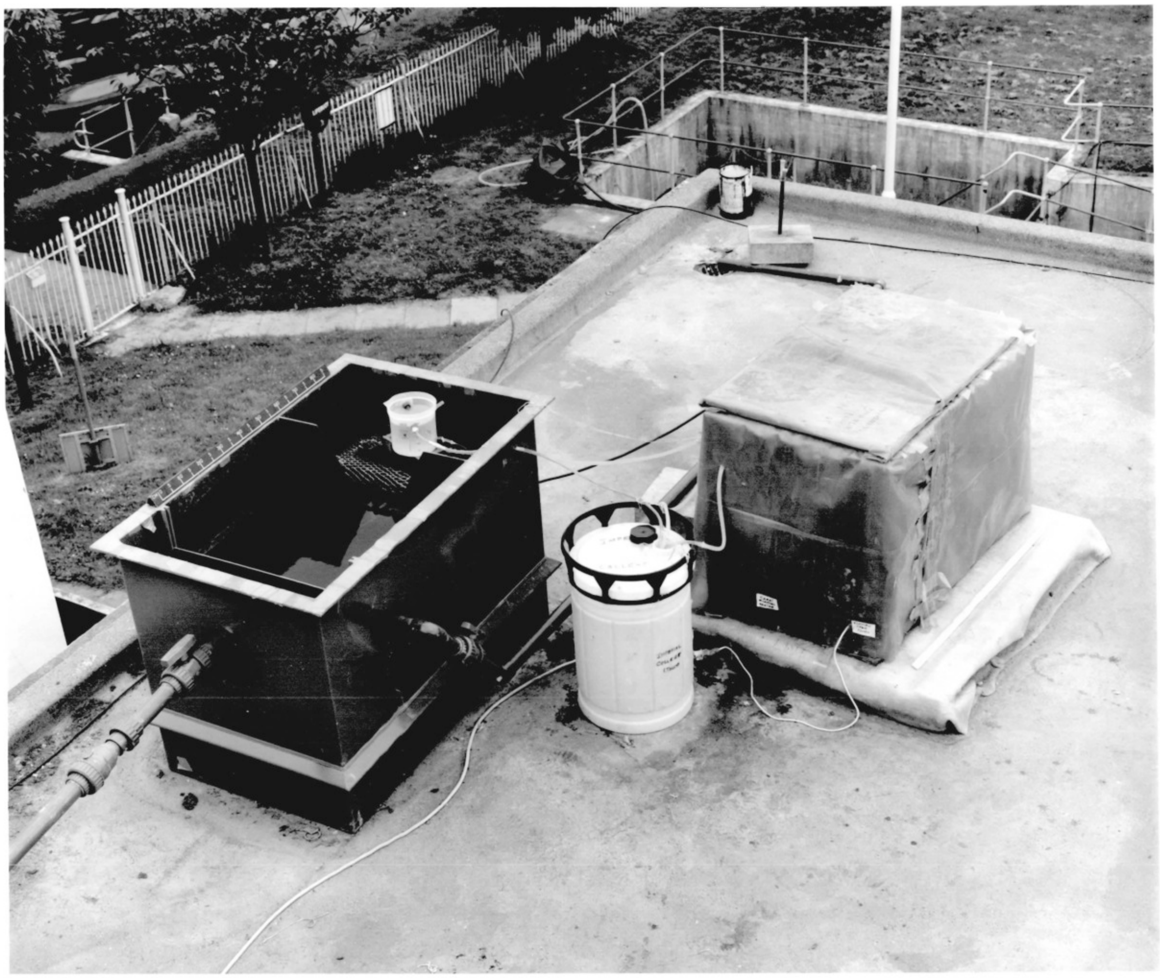


Plate.20 The Chemical Mixing Tank and PAC Container at Egham Pilot Plant .

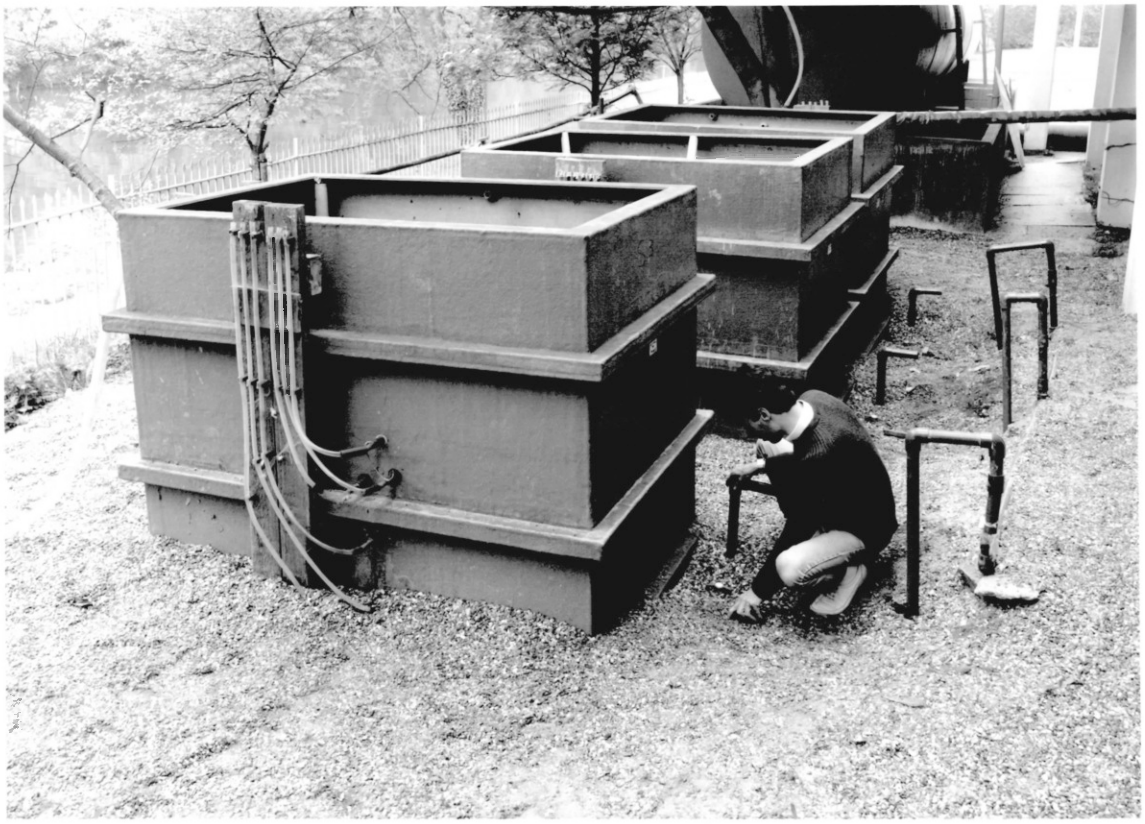


Plate.21 A Side View of the Slow Sand Filter Units at Egham Pilot Plant .

The SSF filtrates were then combined and led to the drain. Note that the two clarifiers were referred to as C1 and C2 while the filters were denoted by S1, S2 and S3 as shown on Fig. 7.3 .

7.1.4 **Filter Media**

The effective diameter of SSF sand used (d10) was 0.30 mm and the uniformity coefficient (d60/d10) was 2.1 . On the basis of the results of field tests done at Ashford Common (reported in chapters 4 , 5 & 6), only NWF lab. No. 28 and No. 32 were used during this study. Table 7.1 gives a summary of the basic properties of the two fabrics. The manner in which these filter media were used is explained in section 7.3.

Table 7.1 NWF Characteristics

Property	Fabric Lab. No.	
	28	32
Fibre composition*	PP	PE/PVC/PA
Fibre diameter (μm)	33	50/40/40
Nominal thickness (mm)	4.8	13
Fabric porosity (%)	89	98
Specific surface area (m^2/m^3)	13,266	1,671

* PP - Polypropylene
PE - Polyester
PVC- Poly-Vinyl Chloride
PA - Polyamide

7.2 Raw Water Quality

Table 7.2 gives the physico-chemical and bacteriological quality of river Thames at Egham main works intake during the period 1984 - 1987 as analyzed by the North Surrey Water Company quality laboratory (130 - 132). Although the mean turbidity and colour values were low, the periodic fluctuations were quite substantial. As regards the bacteriological quality, the maximum recorded values show that the river is generally highly polluted. Chl-a analysis of river water showed peak values during spring and summer. However, in 1986 there was one late peak in autumn (September/October). Between 1984 and 1987, the Chl-a peaks ranged from 130 to 350 mg/m^3 with minimum values of less than 10 mg/m^3. From 1986 to August 1988, the raw water Total Organic Carbon (TOC) ranged from 2.66 to 5.07 mg C/l while the mean value was 4.01 mg C/l. Note that the reference day (i.e. day number zero) for monitoring water quality was on the 30/11/87. While Fig. 7.5 shows the variation of raw water turbidity, Fig. 7.6 shows the variation of pH for the same. Fig. 7.7 shows the average particle size distribution of river water as analyzed by a 400 μm diameter orifice tube on a Coulter counter.

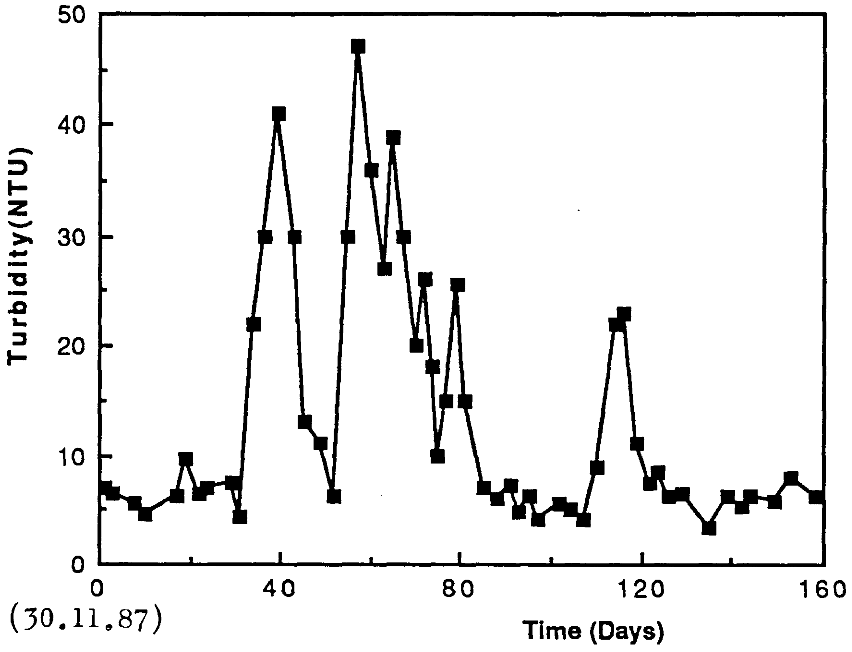


Fig. 7.5 Raw Water Turbidity Variation.

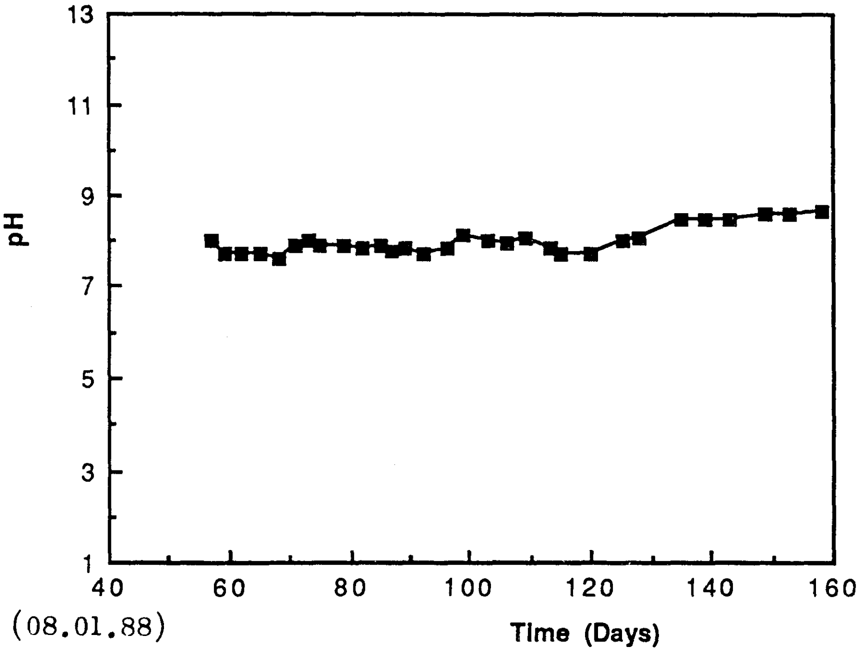


Fig.7.6 Raw Water pH Variation.

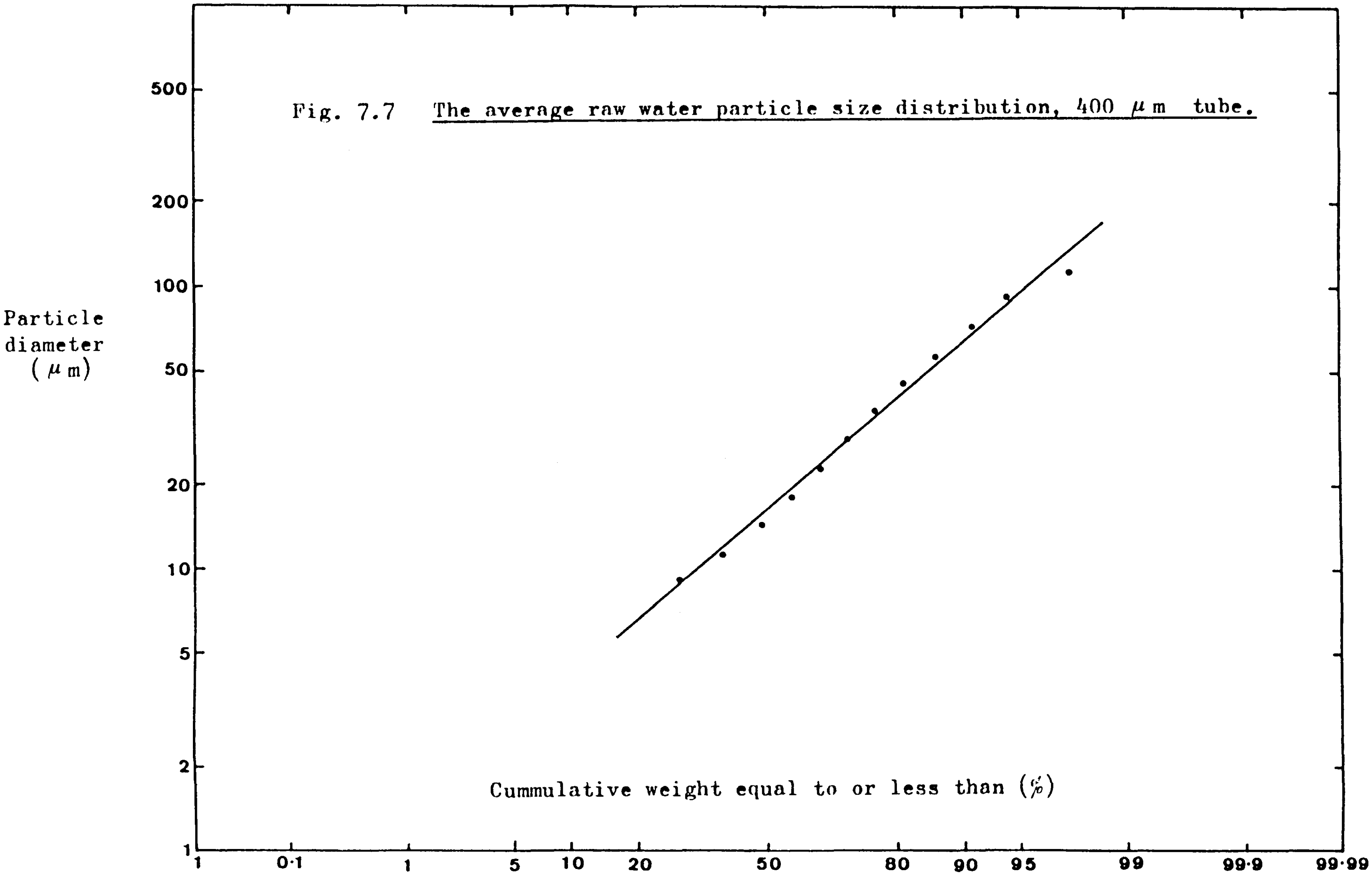


Fig. 7.7 The average raw water particle size distribution, 400 μm tube.

Table 7.2 Quality of River Thames at Egham main works Intake (1984 - 1987).

Parameter	Maximum	Minimum	Mean
Turbidity (JTU)	97	1.8	11.4
pH	8.9	7.4	8.0
Conductivity (μs/cm)	700	520	624
Nitrates mg/l as N	15.7	4.3	8.4
Nitrites mg/l as N	0.226	0.010	0.067
Ammonia mg/l as N	1.02	0.01	0.15
Colour (Hazen Units)	46	3	13
Chlorides mg/l as Cl	59	29	40.5
Sulphates mg/l as SO_4	72.2	48.2	61.4
Permanganate value (mg O_2/l)	9.7	1.0	3.3
Dissolved O_2 sat. rate (%)	129	62	97.5
Phosphorus mg/l as P	2.14	0.32	1.04
Dissolved Iron (μg/l) as Fe	677	10	70
Manganese (μg/l) as Mn	46	5	9.5
TOC (mg C/l)*	5.07	2.66	4.01
Coliforms (No/100 ml)	310, 000	800	-
E. Coli (No/100 ml)	20, 000	25	-

* Only from 1986 to August 1988.

Source: Reference No. 130 -132

7.3 General Conduct of the Experiments

The clarifiers were commissioned on the 30/11/1987, the reference day for water quality parameters monitoring. For SSF, the first day of operation was on the 30/12/1987. During this study, two sets of filter media configurations were investigated as detailed in table 7.3 . Phase 1 simultaneously compared the performance of two types of fabric protected SSF units provided with approximately the same fabric thicknesses with a conventional unit having 600 mm depth of sand only. Phase 2 involved optimization of fabric thickness and configuration. The unit with 3 layers of fabric lab. No. 28 was introduced in order to check whether it was really necessary to use 5 layers as done in unit S1. The configuration of 2 layers fabric lab. No. 32 over 3 layers of fabric lab. No. 28 was meant to combine the high storage ability of lab. No. 32 with the better capture efficiency of lab. No. 28 in order to collect particles which would penetrate through lab. No. 32 .

As regards the PAC dose in the pilot plant , no optimization experiments were carried out because the intention was to produce a clarifier effluent with substantial floc carry-over in order to model poorly operated full-scale clarifier units. Consequently, doses used in the main works were taken as the guideline for pilot plant operation to start with. Thus, in December 1987, the main works average PAC dose was 4.0 mg/l (as Al_2O_3) but during spells of heavy rain which led to increased river water turbidity, the dose was sometimes increased up to a maximum of 10 mg/l . On the basis of these observations and also on actual inspection of the blanket formed in the pilot plant clarifiers, the average PAC dose was usually kept at 6.0 mg/l (as Al_2O_3). During spells of heavy rain, the dose was increased by a factor of about 1.3 .

Table 7.3 Fabric Specifications for the SSF.

SSF Unit	30/12/87 - 07/03/88 (Phase 1)	08/03/88 - 07/05/88 (Phase 2)
S1	5 layers NWF No.28 (Z = 24 mm)	5 layers NWF No.28 (Z = 24 mm)
S2	2 layers NWF No. 32 (Z = 26 mm)	3 layers NWF No.28 (Z = 14.4 mm)
S3	No Fabric (Reference)	2 layers NWF No.32 over 3 layers NWF No. 28, Z = 40.4 mm.

Z = Total fabric thickness.

7.4 Procedures and Analysis Methods

7.4.1 Operational Procedures

Preliminary investigations of surface overflow rates and inlet valves coarseness suited the operation of clarifiers C1 and C2 at rates of 1.7 and 2.0 m/h, respectively. During this period, the depth of sludge blankets was kept at only 10 cm from the top water level in the clarifiers in order to ensure sufficient flocs carry-over to the SSF. During both phases, the SSF units were generally operated at a constant rate of 0.15 m/h which was usually preceded by one day operation at about 0.10 m/h following cleaning of the fabrics and/or filter bed. During the initial start-up in December '87/January '88, all units were operated at a rate of less than 0.10 m/h prior to gradually increasing it up to 0.15 m/h over seven days in order to allow for biological maturation of the filter beds. This is one of the reasons as to why the initial filter runs in phase 1 were not used for evaluation of average filter run times.

During phase 1, at the end of the filter runs the reference filter (i.e. S3) was cleaned by scraping the top 40 mm of sand in order to ensure removal of the majority of deposited impurities. Usually, new clean sand was refilled in the unit prior to re-starting. As regards the other two fabric protected units (i.e. S1 and S2), depending on whether or not substantial penetration of impurities into the sand bed was detected by visual observation (and confirmed by the head loss data), the top 40 mm of sand was scraped and the units were always refilled to the original level prior to being restarted. During phase 2, the decision to scrape sand or not was also based on the check measures applicable to the fabric protected units in phase 1 . During both phases, regardless of whether the sand was scraped or not, the fabrics were always cleaned at the end of the filter runs. Unfortunately, no sand profile silt content or POC analysis could be done during the research work reported in this chapter.

7.4.2 Sampling

Routine samples of raw river water, clarifier effluent and SSF filtrates for pH, turbidity, bacteriological and colour analysis were taken. In addition to these analyses, particle size distribution was analyzed at least once per week. Temperature measurements of raw water in the chemical mixing tank, clarifiers and SSF units were done daily. Diurnal maximum and minimum ambient (air) temperatures were also recorded on a daily basis. Both the water and air temperatures were taken at approximately the same time of the day.

7.4.3 Methods of Analysis

The methods of analysis for each parameter were as follows:

(i) pH - By a probe connected to an Orion Research Ioanalyzer, model 407A .

(ii) Turbidity - On a Hach, model 2100A turbidimeter, (Camlab, UK), measured in NTU .

(iii) Temperature - Water and ambient air temperature was measured on a mercury thermometer capable of registering a temperature range of 40 to -10 ^{o}C. The diurnal maximum and minimum air temperature thermometer was capable of covering the range of 40 to -20 ^{o}C.

(iv) Bacteriological Quality - Faecal Coliforms analysis by membrane filtration technique using the "Delagua" field testing kit, University of Surrey, Guildford, UK (126). Duplicates of each sample were analyzed and the average results reported in No./100 ml.

(v) Colour - Only apparent colour was analyzed on an LKB Biochrom Ultrospec 4050 spectrophotometer at 400 nm wavelength according to ref. (133) .

(vi) Particle size distribution - This was done with a TAII/PCAI Coulter counter using diameter 100 and 400 μ m orifice tubes for routine analyses. For characterization of the particle size of clarifier effluents, diameter 50, 140, 280 and 400 μ m orifice tubes were used to carry out the multiple-tube analysis (116).

The six manometer tubes provided in each SSF box were used to monitor the head loss across the filter media during the filter runs.

7.5 Results

The results are discussed under four main sections which include; hydraulic performance, water quality improvements/changes, filter media cleaning and fabrics washability. During phase 1, the SSF unit protected with 2 layers of fabric lab. No. 32 (i.e. S2) allowed penetration of substantial amounts of impurities into the sand bed and hence at the end of the runs, both the fabric layers and sand were cleaned. The unit S1 protected with 5 layers of fabric lab. No. 28 captured the majority of impurities within the fabric layers and since head loss data confirmed this observation, only the fabrics were cleaned at the end of the filter runs. During phase 2, since no visible impurities were observed in the sand beds of all three units and the head loss data did not indicate existence of penetration into the sand beds, at the end of the filter runs only the fabrics were cleaned.

7.5.1 Hydraulic Performance

The hydraulic performance is discussed separately for phases 1 and 2 in view of the differences in filter media configurations.

7.5.1.1 Phase 1

7.5.1.1.1 Filter Run Time- Reference should be made to table 7.3 for filter media composition in the three SSF units. Table 7.4 gives the filter run times of the three filters during the initial phase. Note that the end of the filter runs was based on inability to operate at the design filtration rate with the effluent valve fully open. The results show that fabrics offer a very good protection to SSF receiving water with flocs carry-over. As a result of this the filter run times of fabric protected SSF units were significantly longer than the conventional SSF. Occasionally, excess carry-over of flocs into the SSF units occurred due to inadvertent blockage of the sludge extraction lines. During such incidences, the fabric protected filters showed an excellent resilience against increase in the rate of blocking the filter media. Under such circumstances, the weakness of conventional SSF became very apparent as the unit S3 blocked within a matter of a few days only. On the basis of the mean results given in table 7.4, fabric lab. No. 28 increased the filter run time by a factor of 2.8 while lab. No. 32 did so by a factor of

3.4 . However, the penetration of impurities through lab. No. 32 and the subsequent sloughing of the deposited matter upon lifting were once again the major factors against its use as a sole fabric layer above sand beds.

Table 7.4 Phase 1 Filter Run Times

SSF Unit	Fabric(s) Used	Successive Filter Run Times (h)	Remarks
S1	5 layers 28	552*,245,416,164* (Mean=331 h, 13.8 d′)	Excess flocs carry - over during last filter runs.
S2	2 layers 32	522*,444,505,116* (Mean=397 h, 16.5 d′)	
S3	None	284*,119,96,115,70*, 120,93,118,68*,92 (Mean=118 h, 4.9 d′)	Excess flocs carry - over, 5th & 9th runs

d′ = days h = hours

*Not used for evaluation of means

7.5.1.1.2 Filter Head Loss - Figs.7.8 and 7.9 show the first filter runs for S1 and S3. While it is clear that almost all impurities were captured in the fabric lab. No. 28 in S1, as expected, the conventional unit S3 captured the majority of its impurities in the top few millimetres of the sand bed. Note the high contribution of the maturation period to the first filter runs and especially for S3 in this case. This is one of the reasons as to why the first set of runs in phase 1 were not used to evaluate the mean filter run time. Figs. 7.10 through 7.12 show the head loss profiles of the second filter runs for all the SSF units.

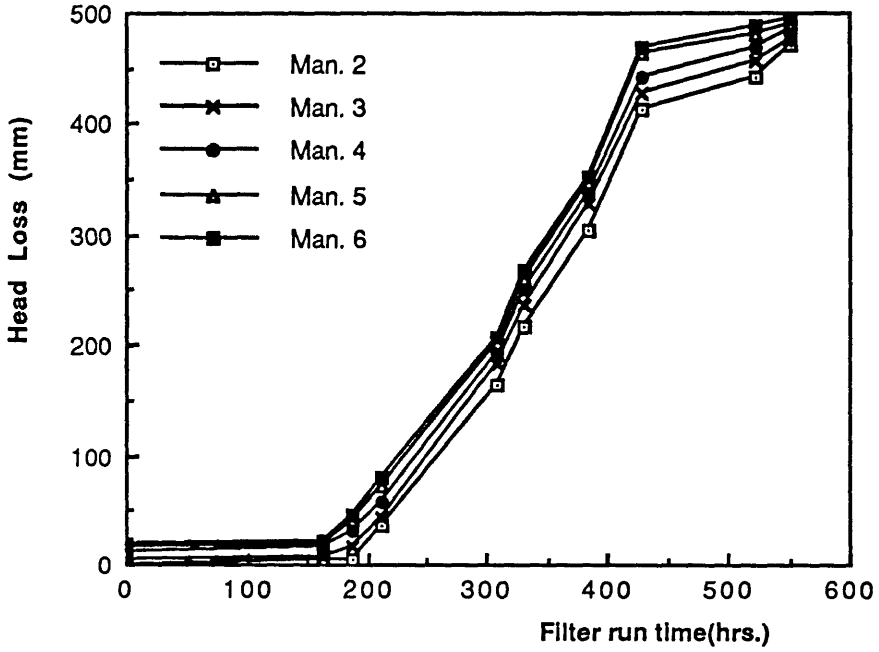


Fig. 7.8 S1 Filter Head Loss (Run 1).

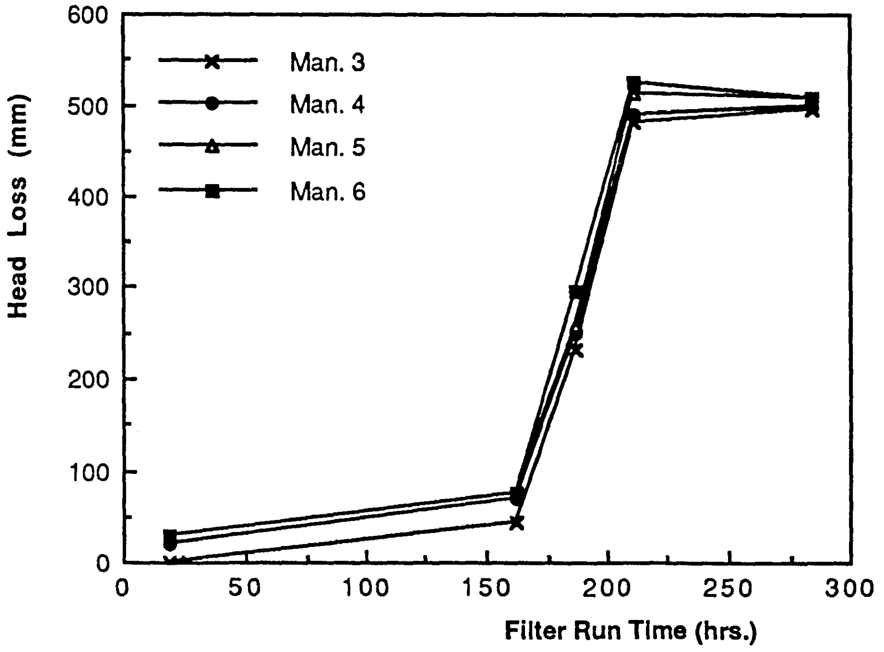


Fig. 7.9 S3 Filter Head Loss (Run 1) .

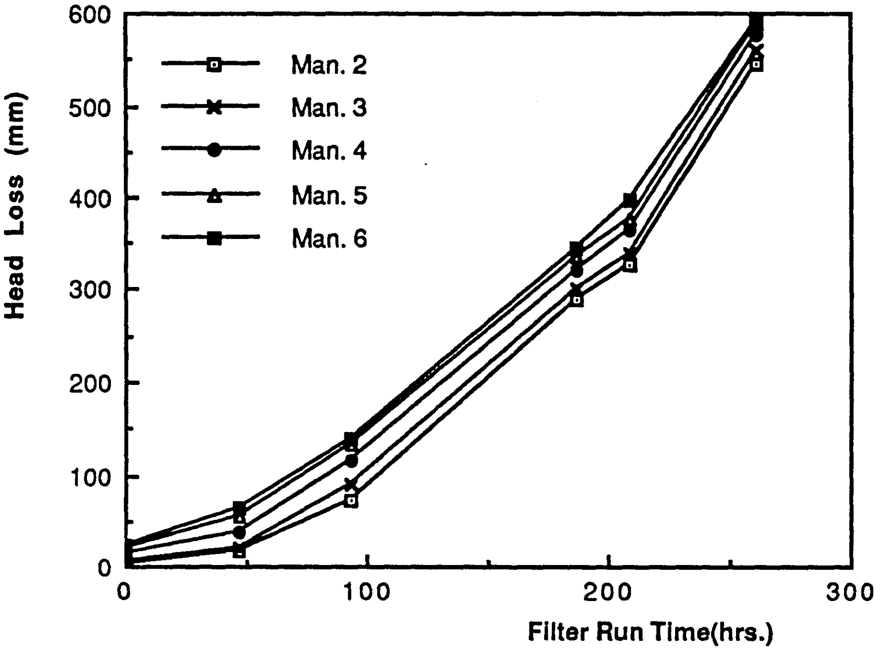


Fig. 7.10 S1 Filter Head Loss (Run 2) .

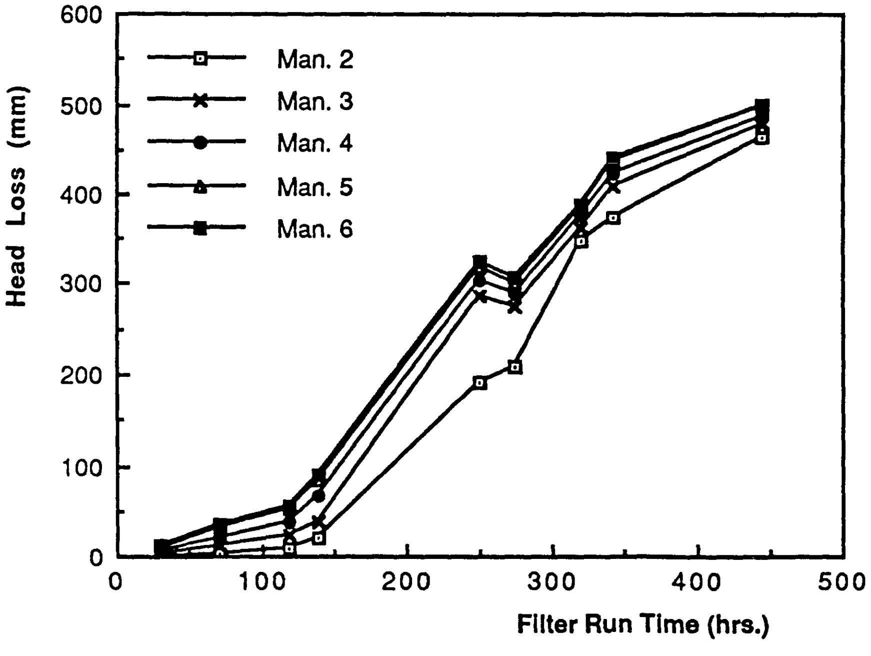


Fig. 7.11 S2 Filter Head Loss (Run 2) .

Fig. 7.10 shows a head loss profile which indicates capture of virtually all impurities in the NWF multi-layer due to manometer No. 2 registering nearly all the head loss. Although Fig. 7.11 shows that the filter run time extension was substantial, the gap between manometer No. 2 and No. 3 is probably an indicator of penetration of impurities onto the sand bed observed in the field. Note the mini-head loss recovery which occurred between 200 and 300 hours in S2 . Fig. 7.12 shows the typical surface filtration nature of the reference unit S3 while Fig. 7.13 shows a head loss profile of the fourth filter run of unit S1 protected with 5 layers of lab. No. 28 indicating capture of virtually all impurities within the fabric multi-layer.

7.5.1.2 Phase 2

7.5.1.2.1 Filter Run Time - Table 7.5 gives the filter run times of the SSF units during the second phase. In general, all three SSF sand beds were well protected and apart from minor edge penetrations, there was no need to clean sand at the end of the runs. The only advantage of using five layers of lab. No. 28 in S1 as opposed to three in S2 was the increase in filter run time as shown on table 7.5 . However, the differences in the mean filter run times of S1 and S2 in phase 2 might indicate that some penetration of impurities into the sand bed occurred in the latter unit. It was neither possible to visually establish deposition on the sand bed nor did the head loss data

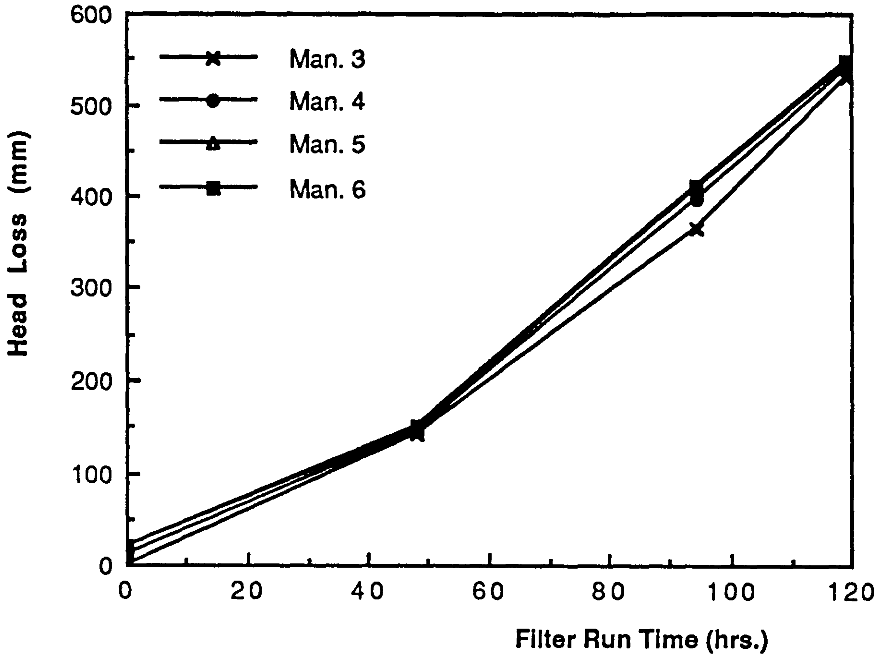


Fig. 7.12 S3 Filter Head Loss (Run 2) .

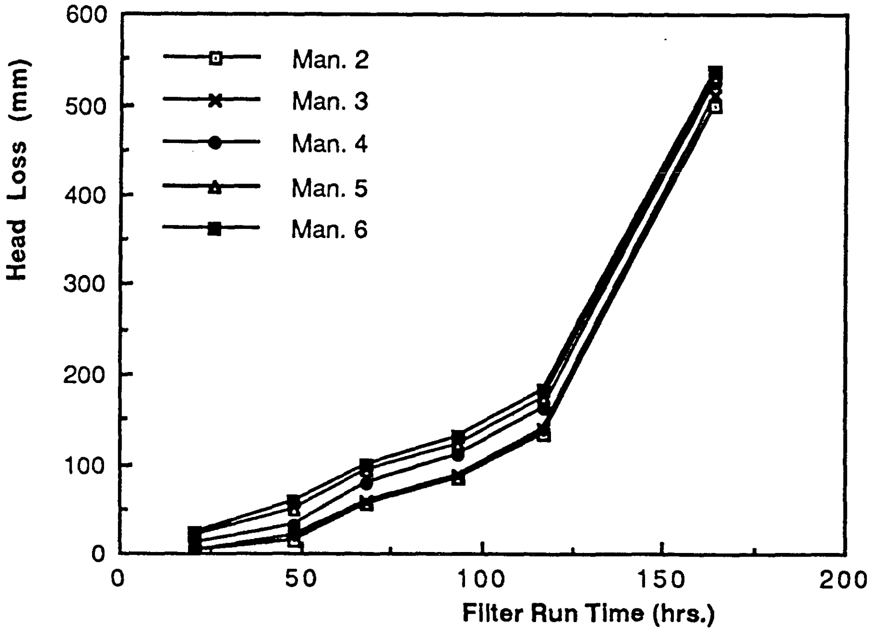


Fig. 7.13 S1 Filter Head Loss (Run 4) .

indicate existence of penetration (if any). In any case, the differences in the number of fabric layers used should be expected to result in different extents of sand bed protection on the basis of the total removal efficiency which is depth dependent for similar filter media. It is likely that the amount of impurities which might have penetrated into the sand bed of unit S2 (if any) were very small. The absence of sand silt content and/or POC data makes it difficult to prove occurrence of penetration of impurities into the sand bed of S2.

Table 7.5 Phase 2 Filter Run Times

SSF Unit	Fabrics used	Successive filter run Time (h)
S1	5 layers 28	281, 354, 331 (Mean = 322 h , 13.4 d')
S2	3 layers 28	209, 332, 295, 278 (Mean = 279 h, 11.6 d')
S3	2 layers 32 over 3 layers 28	631, 528 (Mean = 580 h, 24.2 d')

d' = Days h = Hours

The ratio of average filter run times for S3:S2 and S3:S1 were 2.1 and 1.8, respectively. This proved the superiority of the composite layers over the other two. However, it must be noted that the total fabric thickness of S1, S2 and S3 were 24, 14.4 and 40.4 mm, respectively and the extents of filter run extension were in the order of the total thicknesses.

7.5.1.2.2 Filter Head Loss - During this phase most of the head loss was registered by manometer tube No. 2 in all three units thus showing effective protection of the sand beds. Figs. 7.14 through 7.19 show head loss profiles for the first two runs of all the three SSF units. In all cases, the absence of major gaps between the manometer tubes proved the high level of protection of sand beds afforded. Fig. 7.16 shows that after about 135 hours, the rate of increase of head loss of S2 shot up while Fig. 7.14 shows evening out of the profile such that almost no distinct sudden rise in the head loss can be depicted. Fig. 7.19 shows a profile pattern nearly similar to S1 (Fig. 7.14) in S3 . However, in this case the only notable increase in the rate of head loss development can be identified after about 520 hours. This once again proves the superiority of the optimized NWF configuration in unit S3 which combines the exceptional ability of lab. No. 32 to extend filter run time with the excellent particle capture efficiency of lab. No.28 as observed in phase 1 . The trend of head loss profiles for the second filter runs is fairly similar to the first runs.

7.5.2 Water Quality Improvements/Changes

Water quality changes are discussed with respect to five main parameters monitored. Prior to this, water and ambient air temperature changes are presented.

7.5.2.1 Temperature - This parameter was monitored from 31/12/87 until 05/05/88 . The clarifier effluent and SSF

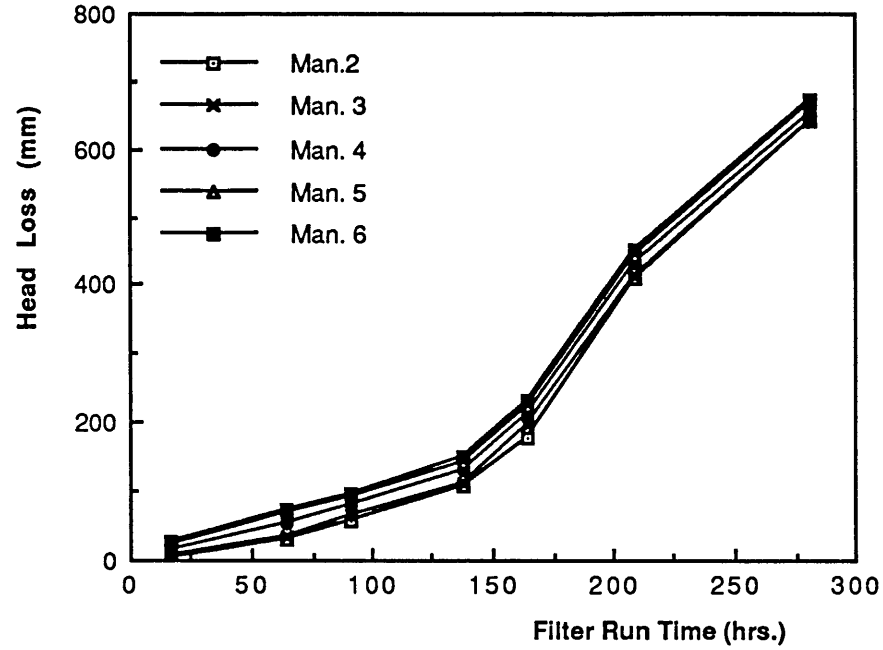


Fig. 7.14 S1 Filter Head Loss (Run 1) .

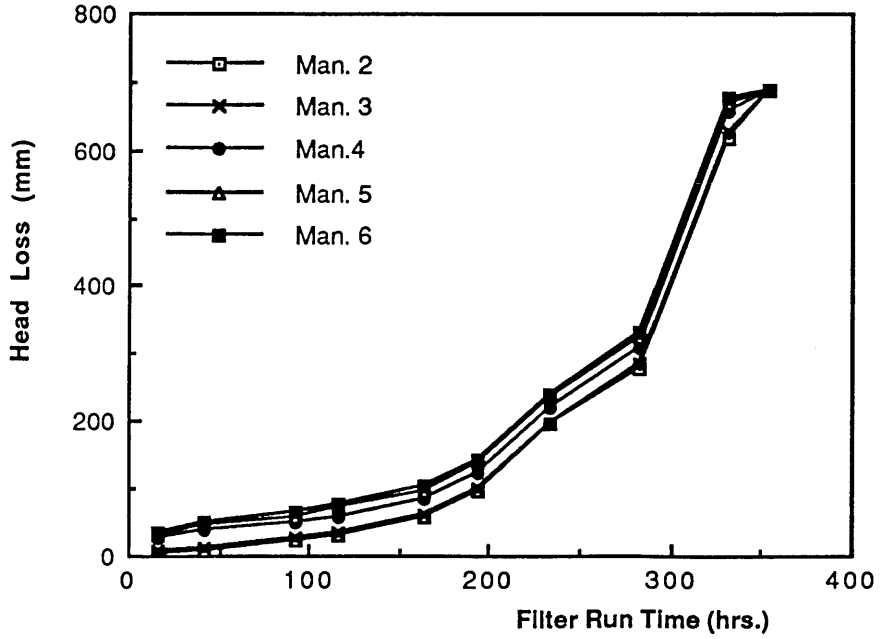


Fig. 7.15 S1 Filter Head Loss (Run 2) .

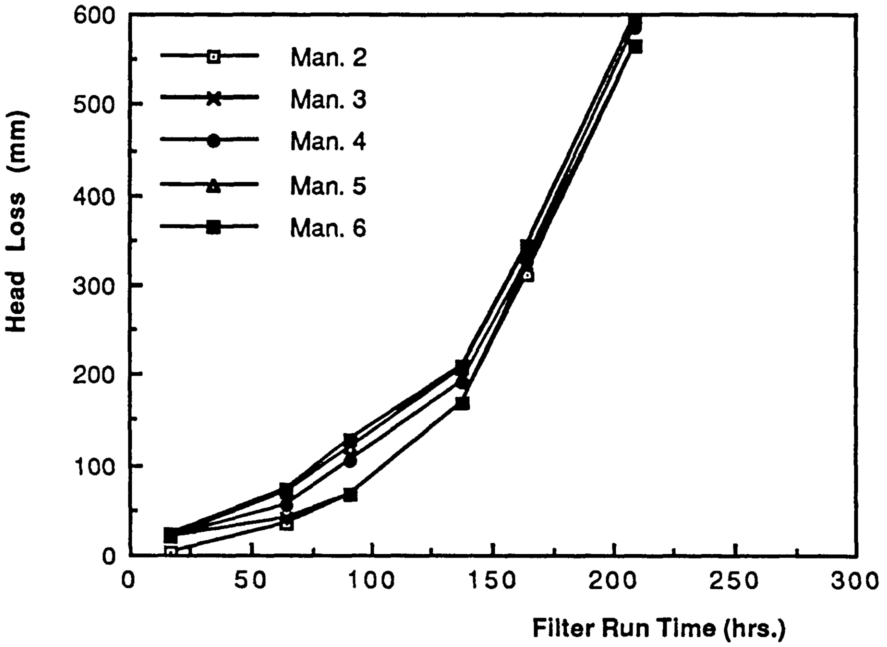


Fig.7.16 S2 Filter Head Loss (Run 1) .

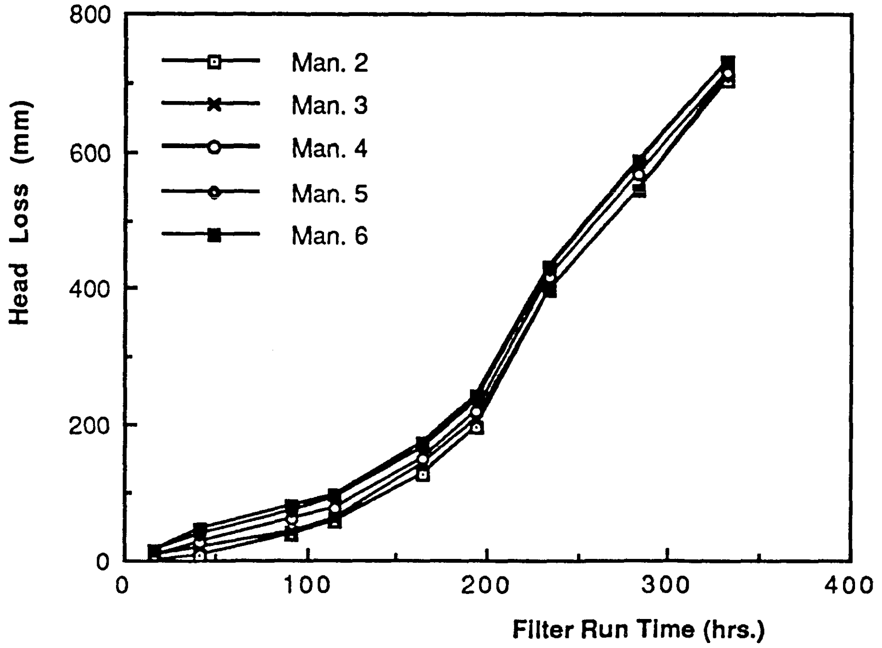


Fig. 7.17 S2 Filter Head Loss (Run 2) .

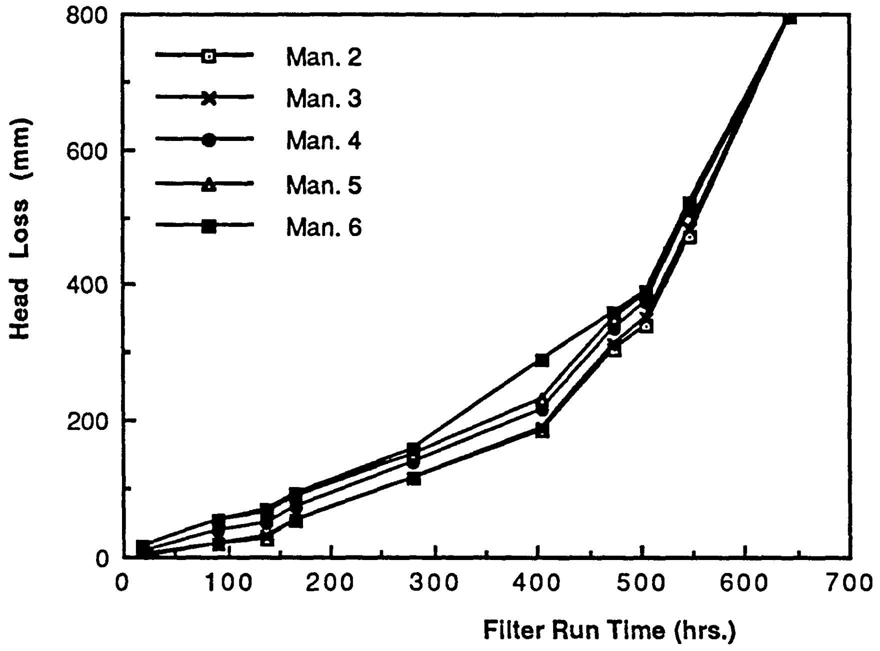


Fig. 7.18 S3 Filter Head Loss (Run 1) .

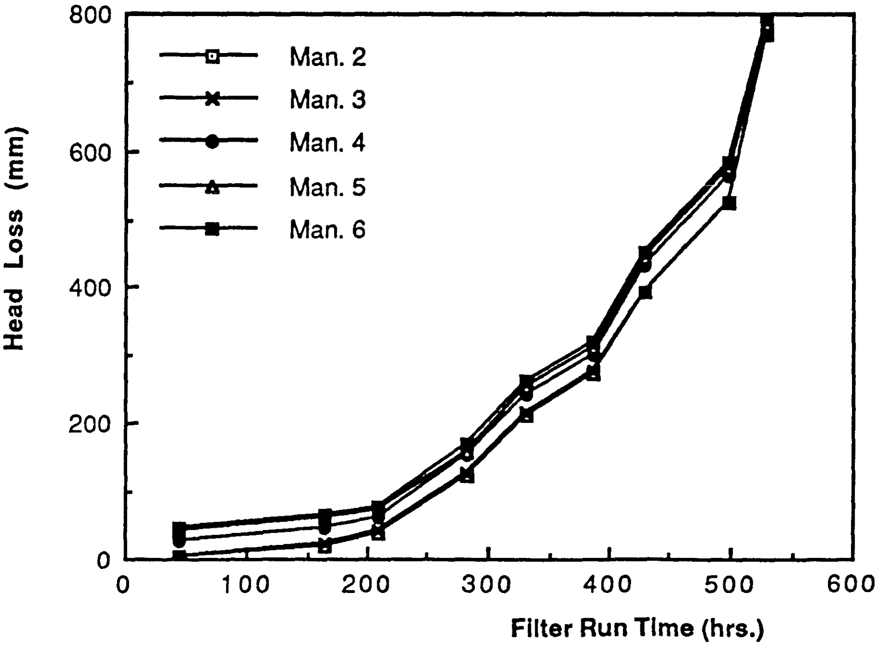


Fig. 7.19 S3 Filter Head Loss (Run 2) .

supernatant water temperature ranged from 3.5 to 13.0 °C. The ambient (air) temperature ranged from 1.0 to 16.0 °C while the diurnal maximum and minimum ambient air temperature measured from 30/01/88 until 05/05/88 were as follows:

Maximum: From + 4.5 to +21.0 °C
Minimum: From - 4.5 to + 9.5 °C

7.5.2.2 pH - From 25/01/88 until 04/05/88, the raw water pH ranged from 7.6 to 8.65 while the pH of the clarifier effluent varied from 6.6 to 7.85 . Low pH levels of the clarifier effluent corresponded to high PAC doses during spells of heavy rainfall . Literature (134), suggests that as opposed to alum or iron salts, PAC can be expected to work well over a much wider range of raw water pH. It is suggested that the most effective range is pH 6 - 9 although satisfactory operations can be obtained between pH 5 and 10.

7.5.2.3 Colour - Apparent colour was monitored only from 06/01/88 until 29/02/88. During this period, the raw water apparent colour ranged from 33.3 to 212.6 Hazen units. The clarifier effluent apparent colour varied from 12.4 to 108.5 Hazen units with higher readings taken after loss of sludge blankets. Typical SSF filtrate colour (sampled from any one of the three SSF units) ranged from 1.3 to 27.9 Hazen units. Therefore in this case, the SSF filtrate colour data was meant to be simply an indicator of typical performance of slow sand filters rather than a comparison between the units. Fig. 7.20 shows the apparent colour removal across the pilot plant. It can be observed that the removals were directly proportional to the fluctuations in the raw water apparent colour.

7.5.2.4 Turbidity - This parameter was monitored from 31/12/87 until 04/05/88. The recorded raw water turbidity ranged from 3.3 to 48.0 NTU with maximum values in January and minimum values in April 1988. The turbidity of clarified water passing to the SSF ranged from 1.0 to 9.2 NTU. This range was wide due to raw water changes and periodic instability in the sludge blankets. All SSF filtrates were never more than 0.60 NTU. Table 7.6 gives the ranges of turbidity of SSF filtrates during both phases. Fig. 7.21 gives the turbidity removal during phase 1 with the reference day as 31/12/87. Fig. 7.22 gives the same for phase 2 with 08/03/88 as the reference date.

Table 7.6 SSF Filtrate Turbidity

SSF Unit	Filter Media	Filtrate Turbidity Range (NTU)
S1	5 layers lab. No.28 (Phase 1 & 2)	0.13 - 0.45
S2	2 layers lab. No.32 (Phase 1)	0.14 - 0.59
S2	3 layers lab. No.28 (Phase 2)	0.14 - 0.32
S3	600 mm Sand Only (Phase 1)	0.13 - 0.32
S3	2 layers lab. No.32 over 3 layers lab. No.28, (Phase 2)	0.14 - 0.41

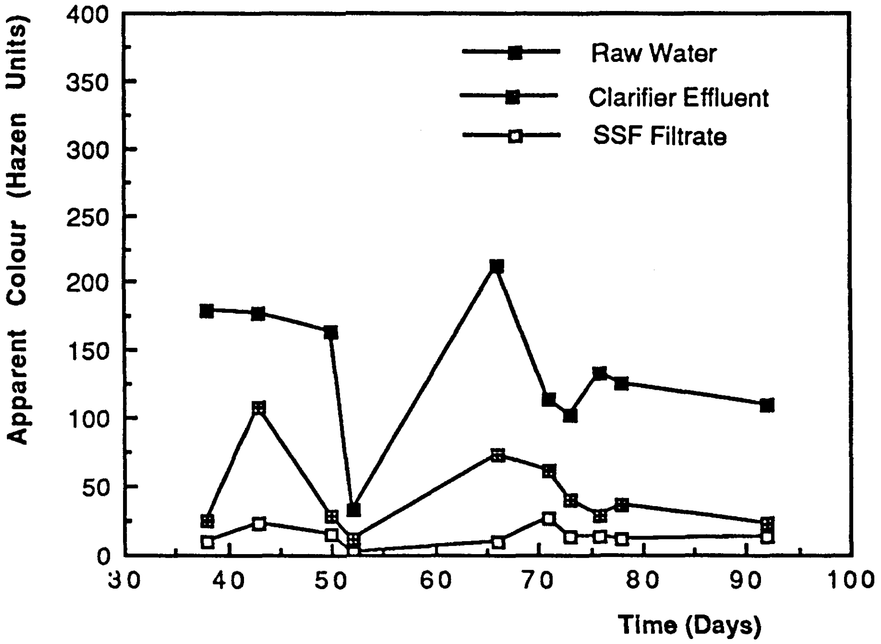
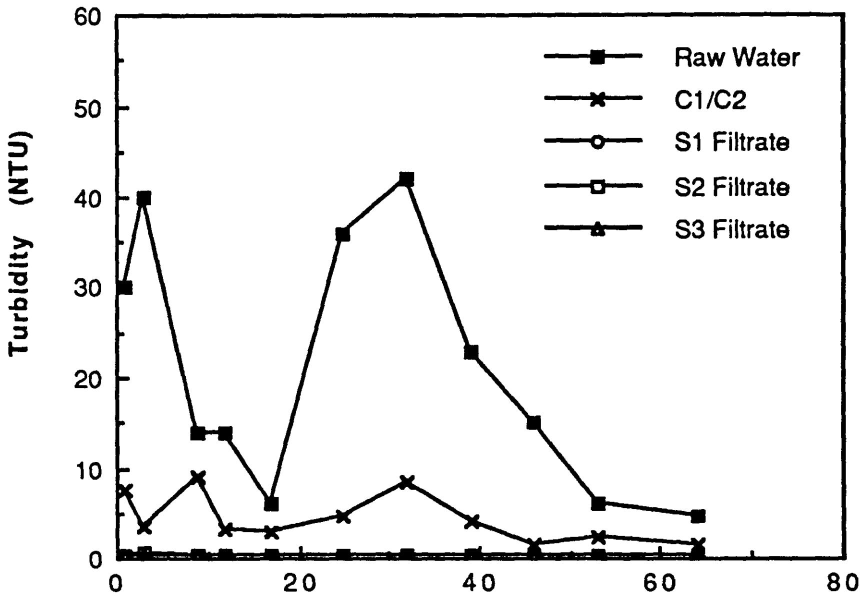
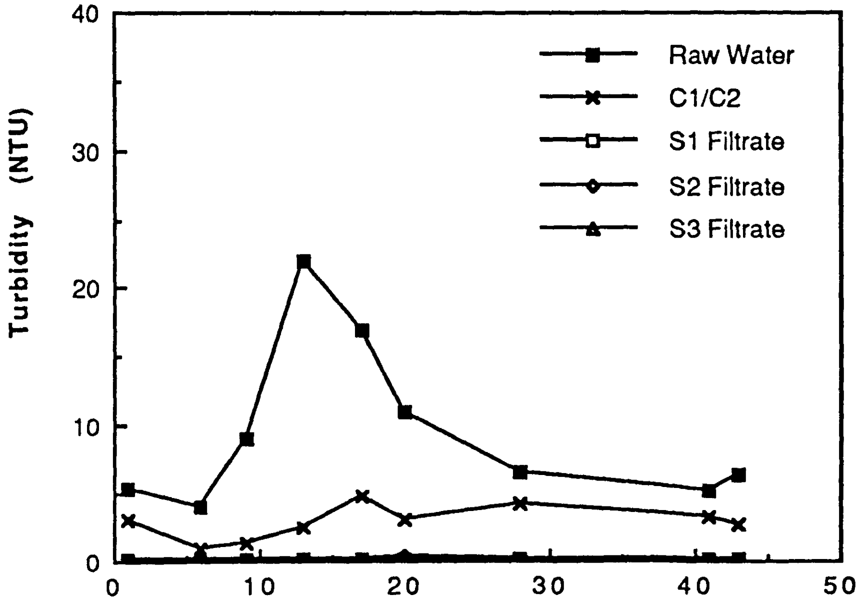


Fig.7.20 Apparent Colour Removal.



(04.01.88)

Fig.7.21 Turbidity Removal (Phase 1).



(08.03.88)

Fig.7.22 Turbidity Removal (Phase 2).

7.5.2.5 Faecal Coliforms - Faecal Coliforms enumeration was done from 03/02/88 to 04/05/88 . During this period, the raw water counts ranged from 965 to 3200 per 100 ml. . The mean removal through clarifiers was 80% with a variability indicated by a RSD of 18.3 %. All SSF units were able to achieve two to three-log reductions in Faecal Coliform concentrations on individual occasions . Counts above 1 per 100 ml were usually detected in the immediate few days following filter cleaning, otherwise counts were typically nil per 100 ml. . Table 7.7 gives the mean Faecal Coliform removal in the pilot plant during both phases. Fig. 7.23 shows the bacteriological quality improvement in the clarifiers. Note the close relationship of clarifier effluent levels with raw water fluctuations of Faecal Coliform counts.

Table 7.7 Mean Faecal Coliforms Removal

SSF Unit	Filter Media	Removals		RSD
		Mean(%)	Minimum(%)	(%)
S1	5 layers lab. No.28	99.4	98.9	0.9
S2	2 layers lab. No.32	99.0	98.4	1.0
S2	3 layers lab. No.28	99.4	98.0	1.1
S3	600 mm sand only	98.75	97.7	1.3
S3	2 layers lab. No.32 over 3 lab. No. 28	99.6	98.5	0.8
Clarif. Effl.	-	80	55.8	18.3

7.5.2.6 Particle Size Distibution - Prior to and during analysis of the clarifier effluent particle size distribution, microscopic observations of the flocs was

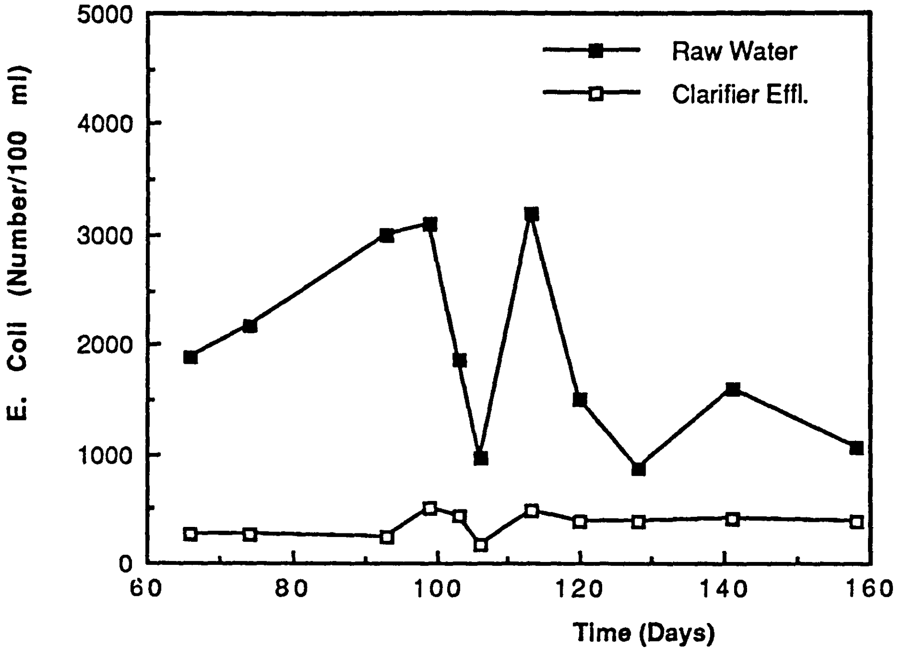


Fig. 7.23 Bacteriological Quality improvement in the Clarifiers

carried out. This was done on an M15C Vickers light microscope at magnifications of x100 and x400 . The eye piece was provided with a graticule divided into 10 grids of either 66 μm or 18 μm depending on whether low or high power magnification was set, respectively. The observation was carried out in order to get an initial idea of the particle size range of flocs and hence help decide on the suitability of the TAII/PCAI Coulter counter with a maximum available orifice diameter of 400 μm for analysis of flocs. Observations showed that the majority of flocs had a diameter of less than 180 μm. A typical maximum diameter of floc agglomerates was found to be about 220 μm. However, a few floc agglomerates were noted to have a diameter of up to 462 μm.

The appearance of most of the particles observed was generally of irregular agglomerates. Observations were done in a chamber of two slides with a wide capillary space in between. From the observed results, the use of a 400 μm orifice diameter tube was regarded to have been suitable since its upper limit of analysis would be expected to cover most of the particles in view of its consideration of the net particulate volume of the flocs. It should again be realized that the microscopic diameter of the particles is not similar to the equivalent volume diameter obtained by Coulter analysis.

Routine analysis of the particle size distribution of raw water, clarifier effluents and SSF filtrates were done from 26/02/88 until 10/05/88. The raw water and clarifier effluent were usually analyzed with a 400 μ m orifice tube while SSF filtrates were analyzed with an 100 μm orifice tube . On two occasions, the particle size analysis of the clarifier effluent was done with the multiple-tube technique for 50, 140, 280 and 400 μm orifice diameter tubes. Fig. 7.24 shows the average cummulative volume distribution for the clarifier effluent as analyzed by the multiple-tube technique. The raw data fits the Log-Normal probability distribution function fairly well.

7.5.3 Filter Media Cleaning

While in the reference (conventional) SSF all impurities were deposited directly in the sand bed, for fabric protected units at the end of the filter runs there always was a small amount of edge penetration of impurities onto the sand. The amounts involved were so small that just localized skimming of the deposited matter around the edges was sufficient. The sludge deposited on the filter media was very difficult to handle when wet, therefore the units were left to drain overnight such that the following day only a small thickness (say 5 - 10 mm) of semi-dry sludge remained on the top fabric surface. Plate 22 shows a plan view of one of the SSF unit after drainage of the supernatant water.

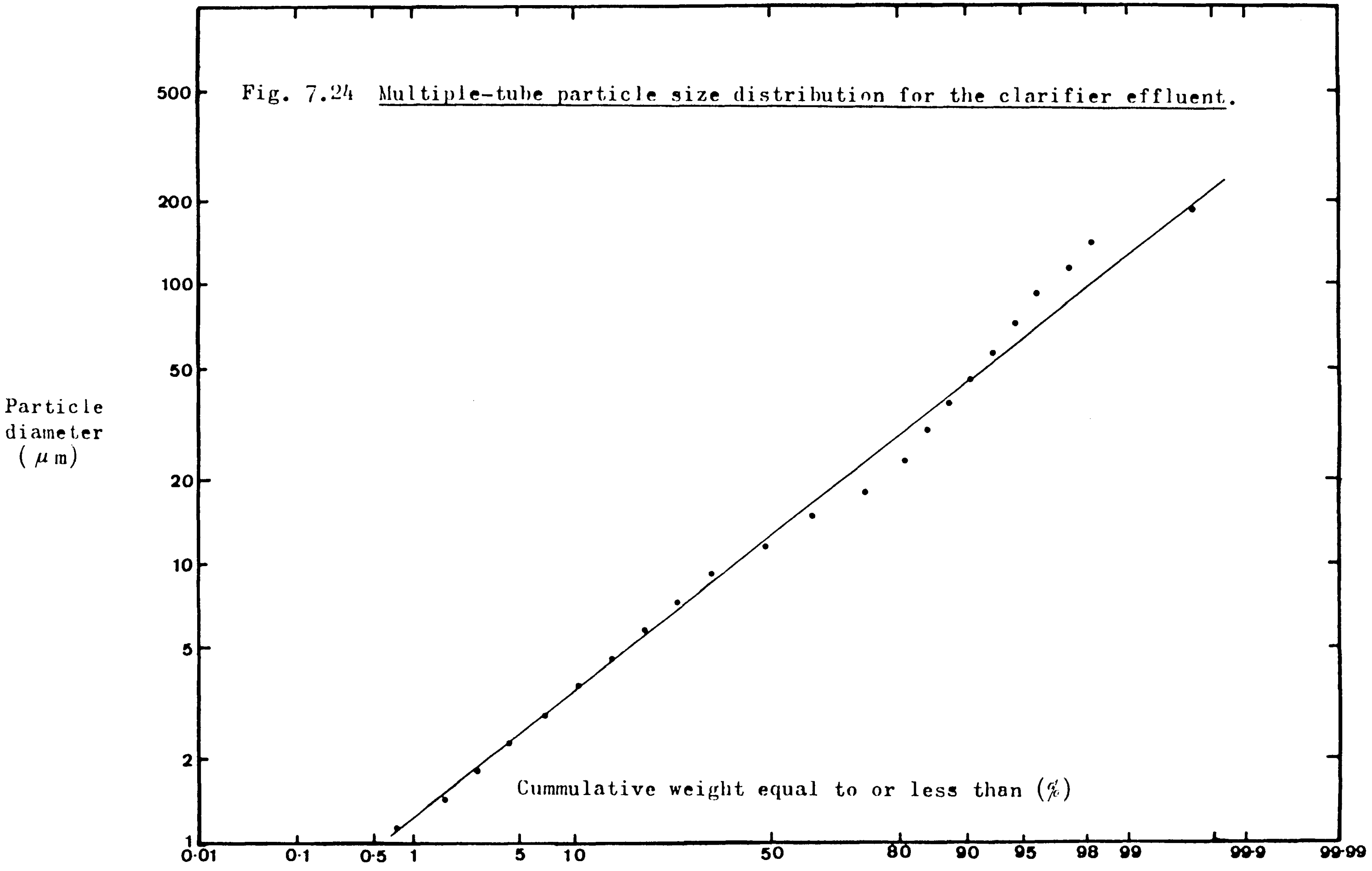


Fig. 7.24 Multiple-tube particle size distribution for the clarifier effluent.

Plate.22 A Plan View of the Fabric Protected SSF Unit After Drainage of Water , Egham Pilot Plant .

7.5.4 Fabrics Washability

At the end of the filter runs the fabrics were cleaned with a high pressure water hose passed over the NWF surface placed against a clean surface. This method of washing proved to be the most effective and seems to open a new direction towards automation of NWF cleaning. Although it was far more easy to clean fabric lab. No. 32 than No. 28, the extent to which the pressure hose could clean both fabrics was quite encouraging. With time, the NWF became gradually tainted brownish. However, the poor mechanical strength of lab. No. 32 might be a negative factor against suitability for long-term use in practise. A possible solution to this is to strengthen the fabric during production in the factory. It should be remembered that this particular fabric is commercially available for air and aerosol filtration .

7.6 Discussion of Results

With respect to filter run times, this study has shown that protection of the sand beds with multi-layers of NWF makes it possible to extend the run times of a conventional SSF by factors of up to 4.9 . This factor is evaluated for both phases 1 and 2 on the basis of equality of the mean filter run times of the unit S1 in both phases (i.e. 13.8 and 13.4 days, respectively). The extension of filter run times can be done by proper selection of suitable NWF type(s), thickness and configuration for the raw water being treated. In the current work it has been possible to use the positive benefits of both lab. No. 28 and 32 to design one multi-layer configuration on the basis of the policy of minimization of required number of individual NWF layers and to produce an optimum configuration in both hydraulic and operational terms.

The main benefit of NWF protection in terms of SSF hydraulics is the ability of the NWF multi-layers to provide a buffer to the head loss profiles such that the occurrence of shooting up of head loss which is described very well by Toms _et al_ (122) either becomes conveniently substantially delayed or virtually non-existent at all. The fact that reasonably predictable head loss profiles can be obtained by fabric protection means that even difficulties in modelling head loss development in the SSF which have been reported (135) might be minimized by the use of properly selected NWF.

As indicated by the head loss profiles and supplemented by visual inspection, all the NWF configurations used during phase 2 were able to retain a large majority of impurities in the fabrics, and as a consequence filter cleaning would therefore only concern the NWF and not involve sand skimming as a routine task. Such a development can result in saving of substantial amounts of operational costs especially if some way of handling and cleaning the fabrics in-situ can be established for large scale filters.

In general, the installation of a NWF multi-layer on SSF beds will not be expected to bring about any notable improvements in water quality as demonstrated by the results of turbidity, colour and bacteriological analysis in this chapter . This is partly due to the very good quality of water produced by conventional SSF.

This study has demonstrated that a fabric protected SSF can cope with poorly operated pre-treatment units which allow a substantial amount of flocs to be carried over to the SSF. These types of problems are common in some developing countries where SSF units are preceded by chemical pre-treatment (39,40). The well known poor ability of SSF to remove colour means that the use of chemical pre-treatment in conjunction with SSF is necessary for significantly coloured raw water sources.

Chapter Eight

8. GENERAL DISCUSSION

The survey of NWF commercially available in the UK which is summarized in table 1.2 shows that their porosity lies between 56 and 99% . While the purely spunbonded and thermic-bonded NWF are characterized by low porosity, the resin spray-bonded NWF show the highest porosity. The several variations of needle-felted fabrics account for the majority of the intermediate porosities. However, it should be noted that although the characterization presented in table 1.2 gives a very useful description of the fabric structural and physical properties, a substantial proportion of the data used for the characterization was supplied by the manufacturers who test the fibres and fabrics without following any standard procedures due to lack of standardization of the testing methods. Therefore, it is advisable to confirm some of the data provided by the manufacturers by carrying out independent laboratory measurements. This was done for all the suspect data provided by the manufacturers during this research programme.

From the review of previous research done up to the end of 1985 when this study was undertaken, apart from Imperial College, the only other group of workers which was still doing some valuable research in the use of NWF to protect SSF was from the University of Surrey (51,81,83). However, a closer look at the nature of the research work done to date by the University of Surrey (UOS) shows that it has not been carried out in a scientifically systematic manner because firstly, there was virtually no sound background or laboratory studies of properties of the NWF which they have used in all their experiments. Secondly, their work has been characterized by the absence of comparative tests between the different filtration and filter media parameters. The general critisism of the previous research work is the inability to set up experimental programmes which would allow elimination or systematic comparison of the fundamental filter media parameters like fabric thickness. The work done by Bridges (63) was purely of preliminary nature and was not supported by any laboratory studies. The only useful contribution of the field experiments done by other workers (42,81,82) so far has been to give some practical experiences about the field performance of the fabric protected SSF of very local nature .

It has already been shown (equation **13**) that the NWF clean media specific surface (S_o) can be defined in terms of the fabric structural and physical properties and specifically the clean media porosity (ϵ_o) and the fibre diameter (d_f). This partially explains why it was necessary to characterize the fabric properties as done in chapter one. The review of the theories for hydraulic characterization of NWF has pointed out the shortfalls of some of the techniques applied by the users of NWF as geotextile filters/membranes. Rollin et al's (92) semi-empirical analytical model of laminar flow through a bundle of fibres/cylinders is dependent upon the knowledge of the structural and morphological properties of the NWF. If simpler experimental methods can be devised to replace the Image analyzer in the determination of the mean distance between the fibres, Rollin et al's model might be expected to become more widely used for hydraulic characterization of NWF.

The review of the cell models has shown that Happel's (97) and Kuwabara's (98) models are suitable for theoretical evaluation of hydraulic conductivity and head loss across NWF. As an example, Happel's model has been successfully used to correlate the permeability factor (k_h) and the clean media porosity (ϵ_o) of the NWF tested in the laboratory (see Fig. 3.18) . Once again, the importance of knowledge of the physical and structural properties of the NWF is necessary in view of the fact that both Happel's (97) and Kuwabara's (98) models produce expressions which are functions of fibre size and fabric porosity. The occurrence of surface-, depth-, adsorptive- or biological-filtration phenomena in a NWF is dependent upon both the characteristics of the suspension to be filtered and that of the NWF.

The filter coefficient (λ) given in equation **(37)** has been postulated to be strongly dependent on the specific surface area of NWF (S) in addition to the overall single fibre collector transport efficiency (η) and the particle-fibre attachment efficiency (α). The dependency of the filter coefficient (λ) on the specific surface has been demonstrated by the laboratory and field tests carried out. However, one must not forget that while it is possible to theoretically forecast the physico-chemical performance of a clean filter media, fabric protection of SSF sand beds involves filtration under conditions where well established biological processes exist. These biological processes can interfere with the surface chemical characteristics of fibres as a result of for example, formation of a biological film on the surfaces of the fibres.

The results of laboratory and field experiments have been statistically analyzed by assuming validity of the normal distributions theory for large parameters or variables . However, for small samples, the student's t distribution was applied. In both cases, variability was measured by the relative standard deviation (RSD) which is sometimes referred to as the coefficient of variation. This is the ratio of the sample standard deviation to the mean. For both distributions, the 95% confidence interval was used for estimation of the confidence of the means. The graphs were plotted on a Macintosh personal computer using the

"Cricket Graph" package (136) available from Imperial College computer centre. The correlation coefficients indicated on the graphs were automatically calculated upon fitting the straight lines .

The observation of NWF by scanning electron microscope revealed many details of the fabric morphology and physical properties of fibres (like holes, diameter variations) which could not have been identified by the naked eye. The fact that scanning electron microscopy confirmed the differences between the properties of the carrier scrims of fabrics lab. No. 27 and 28 illustrates the importance of confirming some of the data given by the manufacturers of the NWF. If SEM analysis was not done, these differences would probably not have been easily picked up. With the exception of fabrics lab. No. 44 and 80, the NWF tested in the laboratory had higher permeabilities than the SSF sand. A comparison of the permeability value of SSF sand and the potential NWF seems to be a good preliminary indicator of suitability of a NWF for the protection of conventional SSF sand beds.

From the results of field tests done at Ashford Common, the NWF lab. No. 44 which was ultimately disqualified on the basis of its inability to extend the filter run time (besides protecting the sand beds effectively) had a permeability value which was less than the SSF sand. The low permeability value is likely to have been due to the high specific surface which is characterized by high fibre density. Although the specific surface is an important guideline for initial selection of NWF for protection of SSF beds, there is a limit above which too high fibre density can make a NWF unsuitable for SSF sand bed protection. This means that the preliminary selection of NWF for the protection of conventional SSF beds should consider both the specific surface and the fabric permeability.

The results of clean media laboratory filterability tests confirmed the strong dependence of the initial filter coefficient on the specific surface. At both filtration rates (i.e. 0.3 and 1.0 m/h), λ_o increased with the clean NWF specific surface. However, other factors like the diameter of particles in suspension, fibre diameter, filtration rate and probably the surface chemical characteristics of the fibres are also likely to have influenced the initial filter coefficient. The manufacturing techniques of NWF can affect the filtration performance of a fabric in view of their influence on the proportion of the total specific surface area of fibres available for deposition of impurities. The laboratory filterability experiments have also shown that most of the NWF are better filter media than sand.

The tests performed at a filtration rate of 0.3 m/h at Ashford Common and reported in chapter four were done under warmer conditions than the other two. The mean water temperature of 16.7 ^{o}C was expected to have encouraged a lot of biological processes in the SSF units as opposed to the mean temperature of 5.93 ^{o}C reported in chapter five. The observed inlet water turbidity was generally lower than during the other two studies undertaken later. The mean inlet water POC and Chl-a during the field tests reported in chapters four and five were exactly similar except for the higher variability in the latter case. This observation indicates that the ecological regimes in the main works supernatant water were fairly stable despite the big differences in the mean water temperatures. The mean water POC and Chl-a removals for the tests reported in both chapters were comparable with no significant differences between the fabric protected units and the reference. The following were the main findings of the results of the work reported in chapter four:

(i)Although the units protected with the fabrics lab. No. 44 provided excellent protection of the sand beds, the inability to extend the filter run time was its main disadvantage.

(ii)Besides the ability of fabric lab. No. 32 (double layers) to extend the filter run time by a factor of up to 3.7, the penetration of the majority of impurities into the sand bed together with the sloughing of the deposited matter upon lifting the fabric(s) were the main disadvantages of using this fabric on its own.

(iii) The substantial decrease of the permeability of fabrics lab. No. 44 and 55 after use for just over three months suggested that the fabrics became blinded with time and therefore they were not suitable for long-term use.

As a result of these findings, tables 1.2 and 3.3 were used to select a lower range intermediate specific surface fabric lab. No. 27 for further field tests which have been reported in chapter five.

The results of the field experiments performed at a filtration rate of 0.15 m/h at Ashford Common and reported in chapter five showed that the best extension of filter run time was provided by the four and six layers of NWF lab. No. 27 both of which nearly doubled the filter runs in comparison to the reference unit. The main distinction between the six and four layers of the NWF lab. No. 27 was with respect to the extent of protection of the sand beds from POC and silt accumulation which was in favour of the six layers as shown in table 5.9 . These findings confirmed that the fabric configuration which offered the best protection of the bed and also the best extension of the filter run time was the six layers of fabric lab. No. 27 . This fabric configuration did not allow sloughing of the deposited matter into the sand bed when lifted up for cleaning at the end of the filter run time. The pattern of accumulation of POC in the sand beds observed during the field tests and reported in chapters four and five was in accordance to the findings of Lodge (86) and Bayley (87).

A survey of the filter run times of the reference units (i.e. with sand only) shows that the AFM2 (main reference) winter run time of 51 days reported in chapter six tied up very well with the AFM3 (as a second reference) winter run time of 56 days and also with the mean AFM2 filter run time of 56 days reported in chapter five. This data together with the rest not mentioned here, confirmed the absence of any major hydraulic performance differences between the sand beds in the pilot plant. This was assumed to have validated the basis of comparison for all the three sets of field tests carried out at Ashford Common.

During the field tests reported in chapter six the mean water temperature was much lower than the same for the tests reported in chapter four. The bacteriological quality evaluated on the basis of faecal Coliforms was much better than during the other two sets of field tests done before. The contribution of the NWF lab. No. 28 in improvement of water quality was assessed by monitoring the performance of five suspended layers of NWF lab. No. 28 in the SSF unit AFM1. The suspended fabric multi-layer was reported (17) to have achieved POC removals of between 52 to 89 % . With respect to turbidity removal, the performance of the suspended NWF multi-layer was fairly similar to the suspended sand layer in unit AFM5.

The most remarkable observation during the field tests reported in chapter six was the extension of the filter run time of AFM6 by a factor of up to 8.4 in comparison to the reference as a result of protection of a conventional SSF bed with six layers of NWF lab. No. 28 . This filter run time extension was attained without cleaning the fabrics or any deterioration of the filtrate water quality. Therefore the performance of the six layers of lab. No. 28 proved that this configuration was the best under the operational and water quality conditions studied at Ashford Common. During all three field tests performed at Ashford Common, there were no significant differences in water quality improvement as a result of protection of conventional SSF sand beds with NWF.

The results of field tests done at Ashford Common were used as a guideline in making a preliminary selection of suitable NWF configuration for protection of SSF receiving coagulated and settled water at Egham. In this case, the provision of a big storage volume within the fabric multi-layer was necessary in order to store flocs during the whole filter run. The use of a composite of lab. No. 28 and No. 32 was considered after establishing that particles could still penetrate the two layers of fabrics lab. No. 32 during "phase 1" of the field tests reported in chapter seven. Under the operational conditions described in the preceding chapter, the configuration of 2 layers of NWF lab. No. 32 placed over 3 layers of lab. No. 28 was tested and found to be the most suitable combination for both extension of the filter run time and sand bed protection.

One of the anticipated situations for application of the treatment scheme with upflow sludge blanket clarifiers and SSF is when treating water with significant colour. In order to show how this treatment scheme can make up for the poor colour removal of SSF on its own, during the experiments reported in chapter seven, the apparent colour removal was monitored. While the average apparent colour removal in the clarifiers was 70.2 %, the average removal in the SSF units was 19.3 %. This accounted for a combined apparent colour removal of 89.5 % which was about 4.6 times the removal efficiency of the SSF alone. Steitieh (137), reported an average true colour removal of 37 % in the clarifiers while the SSF could only remove about 17%.

8.1 Practical Considerations

Since this study investigated the performance of small scale SSF units with a maximum size (plan area) of 2.16 m^2, the experience gained is likely to be more useful for small scale SSF units, say not exceeding 100 m^2. This is because it is felt that the use of NWF in large scale SSF units might present a lot of operational difficulties related to handling and cleaning the NWF. It can be recalled (42,138) that to date, the maximum size of individual SSF units which have been protected with NWF is 28.3 m^2. These were installed by OXFAM in refugee communities as part of a disaster relief system. Even in the case of small scale SSF units, to ease handling difficulties, the NWF will probably have to be placed as strips. In any case, the width of most commercial NWF is limited by the width of the looms. Standard widths of NWF are typically 2 to 5 metres and the maximum total area per roll is just about 100 m^2. Concerning the washing of the fabrics at the end of the filter runs, currently, it has been established that manual pressure water hosing is sufficient. However, there is room for mechanization of fabric cleaning if further investigations are carried out.

The protection of SSF units with NWF is expected to substantially reduce the frequency of scraping the sand bed thus reducing the operating costs of SSF. It is unwise to assume that as a result of fabric protection the sand bed will never have to be scraped or re-sanded. However, in view of the observed very slow accumulation of organic matter and silt in the sand beds as a result of fabric protection, it is conceivable that typically once in a year or two the SSF bed might have to be scraped. The only routine maintenance activity will be cleaning of the NWF. As a result of the consequent extension of the filter run time, even the frequency of cleaning the fabrics will be expected to be vastly reduced if NWF are properly selected as demonstrated in this study.

Subject to confirmation of suitability from the microbiological point of view especially under cold weather conditions, there is the possibility of reduction of the sand bed depth of NWF protected SSF to very nearly the absolute minimum currently suggested to be 300 mm if the NWF configuration is properly designed. This might have implications on the initial costs of SSF which can be reduced as a result of installation of a depth of say 400 mm in place of 800 to 1200 mm currently provided to allow for successive scraping before refilling. The reduced sand bed depth would be expected to polish the water and also act as a second barrier in case of occurrence of wall effects especially towards the end of the filter run time when the fabric becomes nearly completely clogged. If NWF are to be successfully applied to protect large scale SSF, it will be necessary to mechanize the cleaning of fabrics which could probably be done even more conveniently in-situ in order to reduce the fabric handling difficulties which can be expected. In such cases, the use of mechanically sound fabrics would be a pre-requisite.

8.2 Further Research

Further work is recommended to be done to investigate the following aspects:

(i)The efficacy of reducing the depth of fabric protected SSF sand to a minimum dictated by microbiological requirements.

(ii)A separate study shoud be commissioned to establish practical ways of cleaning and handling the NWF in large scale SSF.

(iii)Mathematical models for optimization of NWF configurations should be formulated and validated in the laboratory.

Chapter Nine

9. CONCLUSIONS

The following conclusions can be drawn in relation to the reported work concerning protection of conventional slow sand filters with non-woven synthetic fabrics:

9.1 A full characterization of the range of commercial NWF available in the UK and Europe at large has been made and successfully used to systematically select NWF for protection of SSF units.

9.2 The laboratory and field tests done have demonstrated the strong dependency of the filtration performance of the NWF, or fabric protected SSF, on the filter media specific surface as postulated in chapter two.

9.3 By giving due consideration to both the specific surface and the permeability of the NWF (relative to SSF sand), selection of a NWF which extends the filter run time and also sufficiently protects the sand bed is possible.

9.4 This study has demonstrated how filter run times of SSF treating two different raw water sources can be substantially extended by optimization of the filterability, thickness and the NWF configuration to ensure very low rates of head loss development. As a result of this, filter run time extension by factors of up to 8.4 was attained by protection of a SSF treating long-term stored water subject to micro-straining. For the SSF units receiving chemically pre-treated water with excess flocs carry-over, the filter run time extension factor was as high as 4.9 .

9.5 It has been possible to concentrate the majority of impurities in the NWF multi-layers such that a less frequent routine maintenance involves cleaning of the fabrics only at the end of the filter runs. This was attained in such a way that the filter run time extensions were not compromised as a result of having to capture a large majority of impurities in the fabrics. However, though this work has shown that the sand bed will not have to be scraped at the end of the filter runs, at some future time the accumulation of silt and organics in the bed will probably necessitate scraping or complete renewal of the sand in order to reduce the initial head loss.

9.6 This work has demonstrated that it is possible to design NWF configurations which will not allow sloughing of any matter deposited in the fabrics multi-layer into the sand bed if the fabrics have to be lifted during cleaning at the end of the filter runs.

9.7 The use of a drinking water treatment scheme with coagulation and clarification upstream of fabric protected

SSF units is a feasible alternative when filtering raw water with significant colour in small scale water supply systems.

9.8 This study has shown that although NWF multi-layers can capture a large majority of impurities as demonstrated by turbidity, POC and bacteriological removal, because the filtrate quality of conventional SSF is usually of excellent quality the additional treatment performance of SSF is not significantly improved by the use of NWF on top of SSF sand beds . This observation confirms the results reported by other workers (81,82).

9.9 The present work has shown that for small scale SSF beds it is possible to wash the fabrics by manual pressure water hosing at the end of the filter run times. However, the selection of a NWF for protection of SSF should consider the washing process to be used in order to avoid selection of NWF which are too delicate to withstand long - term washing. A suitable NWF should not suffer from excessive fibre abrasion upon washing as observed with the fabric lab No. 55 during this study.

9.10 To provide a suitable protection of SSF treating water subject to primary filtration (micro-straining) at Ashford Common, the use of six layers of NWF lab. No. 28 is recommended in view of its ability to keep the SSF unit

AFM6 running without even cleaning the fabrics or deterioration of water quality for up to 46 weeks.

9.11 To protect SSF receiving pre-treated river Thames water (from Egham intake) with excess flocs, the use of a composite NWF multi-layer with 2 layers of fabric lab. No.32 placed over 3 layers of fabric lab, No. 28 is recommended in view of its ability to extend filter run time by a factor of about five.

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11. APPENDICES

APPENDIX. 1

```
      PROGRAMME TS.1
      PROGRAMME TO ESTIMATE NUMBERS FROM VOLUME DISTRIBUTIONS
      FABRIC LAB. NO.....L=....MM.,INFLUENT/EFFLUENT,DATE:..........
      DIMENSION M(0:14),P(0:14),DN(0:14),V(0:14)
      PRINT*,'ENTER 15 REAL DELTA VOLUMES AND THE TOTAL NUMBER COUNT'
      PRINT*
      READ*,(V(I), I=0,14),N
      S=0.0
      DO 10 I=0,14
         M(I)=2**(I)
         P(I)=V(I)*M(I)
         S=S+P(I)
10    CONTINUE
      PRINT 66
66    FORMAT(2X,'FAB.NO.',10X,'L=',5X,'MM.',5X,'IN/EF',5X,'DATE',15X//)
      VMAX=S/N
      TDN=0.0
      DO 20 I=0,14
         DN(I)=P(I)/VMAX
         KN=NINT(DN(I))
         WRITE(*,*)KN
         TDN=TDN+DN(I)
20    CONTINUE
      C=(TDN/N)*100
      ITDN=NINT(TDN)
      PRINT 77
77    FORMAT(3X,'I',6X,'V(I)',7X,'M(I)',9X,'P(I)',10X,'DN(I)'//)
      DO 30 I=0,14
         WRITE(*,100)I,V(I),M(I),P(I),DN(I)
100      FORMAT(2X,I3,2X,F8.4,2X,I8,2X,F12.4,2X,F12.4/)
 30   CONTINUE
      WRITE(*,200)S,VMAX
200   FORMAT(4X,'S = ',F12.3,10X,'VMAX = ',F10.6/)
      WRITE(*,300)TDN,ITDN
300   FORMAT(4X,'TDN = ',E15.7,5X,'THEREFORE ITDN = ',I8/)
      WRITE(*,400)C
400   FORMAT(3X,' C = ',E12.5)
      STOP
      END
```

Appendix . 2

Determination of Water POC and Chl-a, Sand Profile POC, Chl-a and Dry Silt Content.

This method is based on the oxidation of Carbon using a Chromic acid solution and titrating the remaining Chromate using Ferrous Ammonium Sulphate :

$$2CrO_3 + 6FeO = Cr_2O_3 + 3Fe_2O_3$$

1. Sand Profile POC, Chl-a and Dry Silt Content

1.1 Procedure

Place 80 g of sand into a stoppered measuring cylinder and add tap water to make up to the 250 ml mark. Vigorously shake the water for 30 seconds and allow to settle. Record the volume of sand excluding any silt (v_s) and water (v_w). Vigorously shake again for 30 seconds and decant the liquid portion i.e. suspension, immediately into 100 ml conical flasks.

With the aid of a Buchner funnel containing a 4cm GF/C filter paper, filter a few mls. of the suspension with the aid of a 1ml. blow-out pipette, the general principle being to filter through as much as possible without clogging the paper. Place the filter paper plus the filtrate into an 100 ml. conical flask and add 7 mls. of strong digestion acid. Cover with a 2.5 cm watch glass and use a minimum of three blank GF/C papers.

Place the flasks on an 105 °C hot plate for one hour and if during digestion the flask contents turn blue, add an additional 7 mls. of strong digestion acid to ensure completion of the reaction. Note the total volume of acid added, and ensure that blanks receive a reciprocal volume. Remove the flasks from the hot plate, add 20 mls. of de-ionized water to each flask and allow to cool. To all the flasks add 3 drops of 1,10 - Phenanthroline Ferrous Sulphate complex solution (Ferroin) 0.025M, and titrate with strong Ferrous Ammonium Sulphate. The sequence of reactions is as follows:

Orange → Green → Blue → "Grey" → Red
End ↑ Point

Finally, to two of the most accurate titrations, i.e. grey/ pale blue colour, add 20 mls. of standard solution. No more indicator is required to titrate the strong Ferrous Ammonium Sulphate.

1.2 Reagents

The Reagents used should be of analar grade and should be stored in amber bottles.

(i) Strong digestion acid:

92 mls. 1.25N $K_2Cr_2O_7$ (40g/l)
188 mls. de-ionized water
5g Silver Sulphate
700 mls. Conc. H_2SO_4

(ii) Strong Ferrous Ammonium Sulphate

13.3 g per litre de-ionized water.

(iii) Standard solution 0.025N $K_2Cr_2O_7$

1.2282g per litre de-ionized water.

(iv) Indicator: 1,10 -Phenanthroline Ferrous Sulphate complex .

1.3 Sand Profile Equations

Assume the porosity of sand is 35 %, therefore the total volume of water = $v_w - v_s + 0.35\ v_s$,

where v_w and v_s are in mls.

The correction factor, F, used to convert all results in terms of cm^{-3} of sand is :

$$F = v_w - v_s + 0.35\ v_s / \ v_s s$$

$$F = (v_w/v_s - 0.65)$$

1.3.1 POC as Carbon

Let : B = Average blank (cm^3)

T = Titre volume for sample (cm^3)

S = Titration for 20 cm^3 of standard 0.025N $K_2Cr_2O_7$ solution .

and v_a= Volume of suspension filtered (cm^3)

$$\text{Carbon present} = \frac{(B-T)\ 1.5\ F}{v_a\ S} \text{ mg C /cm}^3 \text{ sand.}$$

1.3.2 Chlorophyll-a

Filter as much as possible of the suspension decanted into 100 ml. flasks from the POC analysis through a 4 cm GF/C filter paper placed on a Buchner funnel using an appropriate pipette. Fold the filter paper and place it in a glass test tube. Add 95 % methanol solution, heat until boiling and allow to cool for about 30 seconds. After filtration through a sintered glass filter funnel, the extracted methanol is made up to a volume of 15 ml. The methanol is the examined in a UV spectrophotometer at wavelengths of 665nm and 750 nm. The amount of Chl-a present in the sand is then calculated as follows:

Let: A1 = Absorbance of sample at 750 nm.

A2 = Absorbance of sample at 665 nm.

B1 = Absorbance of methanol at 750 nm.

B2 = Absorbance of methanol at 665 nm.

v_a= Volume filtered (cm^3)

v = Volume of methanol (cm^3)

L = Path length of cuvette (cm^3)

The relative Chl-a extinction coefficient for methanol is taken to be = 13.9 .

$$\text{Chl-a} = \frac{(A2 - B2) - (A1 - B1)\ \ 13.9\ F\ V}{v_a\ \ L}\ g/cm^3\ \text{sand}$$

1.3.3 Dry weight of silt

The dry weight of an ignited 4 cm GF/C pad is recorded. A known volume of the sand supernatant obtained in POC analysis is then filtered through the paper using a Buchner funnel. The paper is placed in an oven at 105 °C for an hour; at the end of which time it is removed and re-weighed. Finally, the paper is placed on a crucible in an electric muffle furnance at 500 ° C for an hour. The filter paper is again removed and re-weighed. The changes in weight are then used to calculate the quantity of silt present.

Let : W1 = Initial weight of dried 4 cm GF/C paper (g)

W2 = Weight of dried paper plus material (g)

v_a= Volume of supernatant filtered (cm^3)

$$\text{Silt content} = \frac{(W2 - W1)\ 10^3\ F}{v_a} \quad \text{mg silt*/cm}^3$$

* Dry weight

2. Water POC and Chl-a

2.1 Water POC

The procedure is essentially the same as that for the POC determination of sand profile samples. An appropriate volume of water e.g. 10 litres is filtered through a 4 cm GF/C paper and then ashed at 500 ° C for one hour. The only variation from the profile sample is the use of 7 mls of a weak digestion acid and titration with weak Ferrous Ammonium Sulphate. The titration check requires the addition of only 10 mls. of the standard solution to the best titrated samples.

2.2 Water POC

The test for Chl-a in water samples is basically similar to the analysis of sand profile samples.

2.3 Reagents

All reagents should be of analar grade and stored in amber bottles.

(i) Weak digestion acid

28 mls. 1.25N $K_2Cr_2O_7$ (40 g/l)
252 mls. de-ionized water
5 g Silver Sulphate
700 mls. concentrated H_2SO_4

(ii) Weak Ferrous Ammonium Sulphate

4.0 g per litre de-ionized water