6.2.5 Conclusions on synthetic drain envelope design

There are four sets of criteria for the design of synthetic envelopes: 1) retention criteria; 2) hydraulic criteria; 3) anticlogging criteria; and 4) criteria related to the mechanical strength of the envelope material. The last-mentioned have already been discussed in Section 5.6 and are usually not mentioned along with the first three. Nevertheless, it is important that the strength criteria are also taken into account whilst designing and selecting synthetic envelopes.

Retention criteria
Essentially three types of retention criteria were encountered: 1) O_{90}/d_{90} ratios; 2) O_{95}/d_{85} ratios; and 3) a range of ratios using O_{90}, O_{50}, O_{15} in combination with d_{15}, d_{50} or d_{85}. To start with the third type of ratios, these have become more popular in recent years due to advances in determination of Opening Size Distribution (OSD) curves (Section 5.6.9c). The criteria have not been tested extensively (yet) and are not recommended for use without further research. The second type of ratio is common in the US and France but have one main disadvantage and that is the determination of the O_{90}. The EN ISO standard (EN ISO 12956, 1999) recommends O_{90} as the characterising property for filtration by synthetic materials, because the O_{95} can vary considerably as it was found to be generally located on the gentle sloping part of semi-logarithmic OSD curve (Figure 62B).

The type 1 ratios (O_{90}/d_{90}) seem to be the most practical criterion at present, even though some of the values are in conflict when applied as permeability criterion (for instance O_{90}/d_{90} < 1 and O_{90}/d_{90} > 1). Therefore it is advisable not to use this ratio for the hydraulic or permeability criterion, but the hydraulic criteria mentioned below, instead. One can wonder why d_{90} is used rather than d_{85}, which is more common with traditional granular filter designs. Both the d_{90} and d_{85} are generally located in the transition (steep) zone of the semi-logarithmic PSD curve as can be seen from the many PSD curves shown throughout the book, hence the need for a preference is not apparent. Should one wish to use d_{85} rather than d_{90} a conversion factor of 1.2 can be used, i.e. d_{90}/d_{85} = 1.2. Conversion between other soil particle sizes is described in Section 5.5.1 (Table 18), while conversion factors to convert COS are shown in Table 27.

Hydraulic criteria
Three hydraulic criteria are frequently mentioned in the literature: 1) K_{e} > 0.1 K_{s}; 2) K_{e} > K_{s}, and 3) K_{e} > 10 K_{s}. K_{e} is the clear water permeability of the material. The first criterion, K_{e} > 0.1 K_{s}, was later modified to K_{e} > 10 K_{s} \text{m}^{-1}, while the criterion of K_{e}/K_{s} > 0.1 was rescinded. A fourth criterion presented by the French Committee on Geotextiles and Geomembranes (CFGG 1986, 296
Table 35, part M) relates permittivity ($K_e/T_e$) to certain values. Criteria become more stringent in ascending order, hence criterion 1 will be easy to meet (but is not correct), and criterion 4 the least easy. Wilson-Fahmy et al. (1996) demonstrated that although criterion 4 was not met in most cases the site drainage systems worked well (details in Section 6.3.3, Table 36). Criterion 1 has no safety built in, whereas the others do to varying degrees. For agricultural applications it would seem that criterion 3, which is similar to that used with granular envelopes, would be the most appropriate (see also Sections 5.6.10 - 12). Giroud (1996) presented a formula, $K_o > 10 K_s i_s$ including criterion 3 as a function of the exit gradient. In addition to criteria relating hydraulic conductivities directly (using clear water permeability), there are a number of indirect hydraulic criteria such as $O_9 > 0.5 - 1$, $O_9 > 200$ mm, and the criteria from permeameters that use $K_{es}$. The latter include some soil with the filter material (see Sections 5.7.3 - 5). Those that use particle sizes should be used with the envelope design criteria with some caution. Those resulting from laboratory experiments with permeameters should be used qualitatively only (i.e. to compare laboratory results with each other but not to relate directly with field results or incorporate in design criteria).

**Anti-clogging**

Clogging of synthetic fabrics is a decrease of permeability in the long-term caused by particles of the base soil. This is different from blocking of synthetic envelopes, which is the immediate near total loss of permeability of the envelope by a layer of fine particles (commonly caused when smearing under wet construction conditions takes place). At present there are few established criteria and permeability tests are generally recommended (Wilson-Fahmy et al. 1996). Dierickx proposed $O_9 > 200$ µm from a hydraulic and anti-clogging point of view, his theory being to prevent clogging of the fabric itself. Christopher and Holtz (1992) remark that when $C_u > 3$ then use $O_{95} > 3d_{15}$ and when $C_u < 3$ the maximum opening size allowed from the retention criteria should be used. Wilson-Fahmy et al. (1996) found clogging of the drain conveyance medium (pipe or inside of composites) and not much clogging of the fabric itself. Consequently, there is an obvious need for considerable further research on this particular aspect of synthetic envelope design.

**Additional conclusions**

Giroud (1982) mentioned that contact between soil and fabric was not satisfactory if the material has a smooth surface, which lead to mismatch between design criteria and values observed in the field laboratory.

The overriding impression on reviewing the literature on synthetic envelope design is that the design criteria for synthetic envelopes are constantly changing and that the reports encountered are somewhat sloppy in that there seem to be many differences between what are supposedly the same criteria, even
within the same article! In Table 35 we have tried to resolve this mentioning where we could not reconcile the issue. In each of the articles reviewed authors seemed to model the presentation of criteria developed by others to suit their own purpose (and we are probably guilty of this too!). It is recommended that criteria only be reported as originally presented by the researchers, and then and only then (and clearly indicated) rewrite the equation or ratio to fit the particular need.

6.3 Field experiences

There are many articles and publications that report on actual field experiences, but unfortunately many do not present enough detail to compare the results with the criteria presented in various parts of this book. We therefore provided a description of essential data to be reported in Section 4.7.3, in the hope that future publications will provide the desired adequate detail. Alternatively, reports referenced in those articles, which are the basis of the results presented in the paper, can be obtained. Recent developments included in research reports and the like obtainable from databases via the World Wide Web are likely to enhance accessibility to these critical data.

6.3.1 Granular envelope

Case study California

In 1970, after some serious problems with clogging of drain envelopes were discovered in the Imperial and Coachella Valleys of California, an elaborate experiment was designed to test drain envelope materials. More than half of the drains installed in the Coachella Valley had water above the pipes, indicating that the envelope materials or the drain openings were clogged. The experiment was constructed and maintained by the Coachella Valley County Water District and was a cooperative effort with the USDA-ARS and the University of California at Davis. The soil had a fine sandy texture with little cohesion and a considerable mica flake content. Clay, concrete, and perforated plastic pipes were tested with various types of gravel envelopes. Replications included pipes without envelopes. Since the area was very arid, a solid set sprinkler system was used to apply water. Individual valves were installed in the drains so that drainage intensity (drain spacing) could be modelled by closing some of the drain outlets. The drains without envelopes failed quickly. The drains with coarse and fine single sized envelope materials allowed excessive amounts of the sand to enter the drains. Gravel envelope materials with excessive amounts of fines also failed. Envelope materials that had acceptable grading curves and did not have excessive amounts of fine materials performed successfully (Davis et al. 1971).
There were some problems with the envelopes in some locations, and soil contamination of the envelope material was suspected. So, a second experiment was installed in which some of the envelope material was handled according to normal practices, i.e., it was stockpiled on the ground in the field and was loaded into the drainage machine with tractor loaders as needed. The other treatment was to move the material directly from trucks into the machine so that it would not have any chance to become contaminated with surface soil from the field. Drains installed with envelope materials that had been contaminated with soil failed. Drains with clean envelope materials performed successfully. It was apparent that even small amounts of soil will seriously contaminate drain envelope materials because the fine soil particles clog the openings of the envelope material.

**Case studies Pakistan**

Construction of subsurface drainage systems in Pakistan has taken place at five locations since 1971 and several more are scheduled. Details of the granular envelopes at four locations (Fourth Drainage Project, Mardan, East Khairpur Tile Drainage, and Khushab) have been published. Either USBR, SCS or US Waterways Experiment Station specifications (Table 34, parts F, I and J, and B) were used for the envelope design. Although designed according to the specifications, serious problems occurred with the crushed rock envelope at the Fourth Drainage Project near Faisalabad. An in-depth review of existing criteria revealed that the selected specifications for this particular project were on the coarser side of possible gradation specifications.

For the East Khairpur Tile Drainage Project (EKTP), filter criteria as developed by the US Waterways Experimental Station (Dieleman and Trafford, 1976) and used as source by the UK Road Research Laboratory (RRL,
Spalding 1970) were compared with the 1971 Soil Conservation Service (SCS and the 1978 United States Bureau of Reclamation (USBR) criteria. Composite curves resulted (Figure 86) which worked satisfactorily with the gravel materials available at the Shadi Shaheed quarry. At the Mardan SCARP and the Fourth Drainage Projects (FDP) straight forward USBR criteria were applied (USBR 1978). Khushab SCARP horizontal subsurface drainage design was more recent (1991) and for those SCS 1988 criteria were used.

Figure 86 shows the representative curves for lower and upper limits of the base soils and corresponding lower and upper envelope gradation curves for all the projects. The gravel envelope curves of the EKTP are finer than the USBR based curves. Willardson and Ahmed (1988) found that the 1971 SCS criteria result in finer envelopes than the USBR criteria and therefore are more suitable for use as filter criteria. Criteria that further describe the shape of the curves, coefficient of uniformity ($C_u$) and curvature ($C_c$), are also used at FDP and Khushab SCARP. From Khushab SCARP it was concluded that also the SCS 1988 criteria needed adjustment from practical point of view (see Section 6.2.1).

Problems with the crushed rock partly stemmed from construction problems, but when these were resolved crushed rock material still did not perform well. Analysis in the field with specially laid test lines using crushed rock (having angular shaped particles) and river run material (having rounded particles) showed that river run material with the same characteristics on paper, performed much better. Sieve analysis of samples excavated after installation showed invasion of fines in both the crushed rock and river run envelopes. The percentages passing the ASTM sieve no. 200 (0.074 mm) ranged from 10% to 17% in those samples (Figure 83).

While research was still going on, FDP introduced limitations on hydraulic conductivities of granular envelope materials (Vlotman et al. 1995): $15.3 \text{ m/d} < K_e < 153 \text{ m/d}$. Performing a 21-sieve analysis and following the appropriate design guidelines based on prescription for the envelope band should, however, satisfy the $K_e$ criteria in most cases. Laboratory testing of materials straight from the quarries or other sources met with mixed success. Sand alone would not bridge over the perforations if the maximum perforation size was allowed, and crushed rock did not perform as well as some of the blended materials and the river run material. Coarse river run material also did not perform well. River run material from the quarries near Attock performed very well and would fit most gravel bandwidths in SCS 1988 criteria.

Another interesting finding was that no evidence has been found at the two projects where envelopes with high carbonate contents were used pointing to
it being detrimental for the functioning of the granular envelope (Vlotman *et al.* 1995). At EKTP the carbonate content was more than 80%, while the envelope material used with the Nawabshah Interceptor drain contained more than 50% carbonates.

### 6.3.2 Organic envelope

Any voluminous porous organic material can theoretically be used as envelope material around a buried subsurface drain. Such material will improve the hydraulic performance of the drain and could temporarily protect the drain from sediment inflow. However, organic materials may deteriorate in the soil, due to biological degradation, and the drain could lose the protection provided by the envelope material. Many different organic materials have been successfully used as drain envelope materials, but their durability depends on the type of material and the bacteriological environment at the drain level.

**Fibrous peat**

Peat is one of the better organic drain envelopes with an acceptable durability experience. Suitable peat is required to contain a large amount of fibrous material that is not too dusty and does not contain large clods. Use of peat evolved from a simple loose cover over the drain to a netted pre-wrapped material. Adding coconut fibres enables pre-wrapping with synthetic threads. The intermediate form with peat being stitched onto a non-woven carrier strip has been less successful as a result of the high entrance resistance of the fine-structured carrier strip that formed the interface with the soil. Also, soil particle invasion cannot always be prevented when the material was placed under wet conditions, especially when the strip ended up beside the drain. Covering the top of a drain does not suffice to prevent soil particle invasion through the bottom perforations (Dierickx and Leyman, 1978). For efficiency, an additional underlay strip is needed. Peat was extensively used in the Netherlands, but problems with the supply of good quality peat and the fact that prewrapping was more expensive than other organic materials, resulted in its disuse. Among the organic drain envelope materials in common use, peat keeps the longest in soil.

**Flax straw**

Flax straw used for an envelope is the waste that remains after retting flax. After initially being stitched with synthetic threads to a strip to cover the drain, flax straw is then wrapped around the drains at the time of manufacture. The coarse fibre structure requires a thicker layer to offer an adequate protection against soil invasion, but even then flax straw was still found to be too coarse. A strip of the material used only as a cover does not prevent soil invasion from underneath and therefore requires an additional underlay.
strip. The voluminous flax straw envelope has proved to be an excellent material with adequate durability. Although taking second place to peat, research on the durability of flax straw has never been done. The downturn of the flax industry and the appearance of the more favourably considered coconut fibres caused the disappearance of flax straw as drain envelope material in Europe.

Coconut fibre
Coconut fibre (coir) has been considered as a more favourable organic envelope material than flax straw because its structure is not so coarse. However, the $O_{90}$ value for coconut fibre is more than 1.0 mm (1000 μm) which is too coarse for certain fine sandy soils and results in soil invasion in the drains. Another important disadvantage of coconut fibre is its limited lifetime, especially in alkaline soils and soils rich in organic matter (Meijer and Knops, 1977). Its mean lifetime is about 4 to 5 years although coconut fibres can decay within one year (Dierickx, 1985). Coir fibre is an organic fibre consisting of 46% lignin and 54% cellulose (Venkatappa Rao and Balan, 1994). Coir fibre is more resistant to rotting than jute, which has only 11.5% lignin.

Wood chips and saw dust
Wood chips and coarse saw dust originating from a chain saw or commercial sawmill are mainly used as drain envelope materials in the Scandinavian countries, initially as a loose cover and later wrapped around the drain inside a plastic netting material. The bulky application is somewhat labour-intensive and not so effective in preventing soil particle invasion, as the drain is not protected underneath. When used as wrapping it is an excellent material. The durability is not known, but due to the reduced micro-biological activity at lower temperatures in Scandinavia, its lifespan appears to be adequate.

Other organic materials
Obviously there are numerous other organic materials that can be used as a drain cover or as a wrapping envelope for drain tubes, depending on the inventiveness of farmers. These are materials that are mostly only locally available. They have therefore never been used on a large scale and consequently the experience with such materials is very regional and limited. Heather appeared to be an excellent material with high decay resistance. Also straw of cereals, chopped or not, has been used but cannot be recommended because of slime formation when decaying, and the restricted life. Other materials that have been mentioned are: chaff, corncobs, brushes, reeds, moss, conifer leaves and grass sod. A number of articles on the application of jute, coir and sisal as natural geotextiles are in Karunaratne et al. (1994, pp 849 - 902). They go beyond the scope of this publication but may be of interest when considered for use with agricultural drains. Typical topics covered in the articles include: jute application for general civil engineering treated with anti-
microbial agent to extend their life in the soil (India); jute in combination with different ratios of polypropylene fibres for civil engineering (India); jute durability tests (India); jute for vertical drains (Bangladesh); jute geotextile in layered clay sand reclamation (Singapore); sisal fibres for erosion control (South Africa); and application of coir geotextiles for river bank protection and embankment stabilisation (India).

6.3.3 Synthetic envelopes

Glass fibre
Glass fibre was the first material to be used as a strip to protect drain-pipes against soil particle invasion (Johnston, et al., 1963). It can be applied without any difficulty in sandy soil provided that it is not too ferrous or too organic and the amount of fine particles is limited. Glass fibre has been used in non-cohesive soil underneath the drain in combination with a peat, flax or coconut fibre strip placed on top. In this way the soil invasion from underneath was prevented while the voluminous cover strip reduced the flow pressure and the clogging risk. However, when used for clay drains sediment was often found in the drains. Furthermore, field experience demonstrated that the edge of the pipe drains often damaged the glass fibre sheet during installation, and it was concluded that glass fibre did not offer adequate protection to prevent soil particle invasion (Dierickx and Leyman, 1978).

Efficient protection was obtained when glass fibre was used in combination with plastic drains. Because of its fine structure, glass fibre was found to be vulnerable to blocking and clogging by fine soil particles, organic dust, and from iron ochre, and therefore cannot be recommended as drain envelope in many soils. These disadvantages and the fact that it irritates the skin of the labours during processing are the reasons why glass fibre is no longer used. If a fine envelope is considered to be useful, fine non-woven geotextiles are used. Only boro-silicate glass should be used as other glass fibres dissolve in the soil environment.

Glass wool
Glass wool mats are 1 to 2 cm thick. For this voluminous material, clogging is less critical than for fibreglass, especially for glass wool with coarse fibres. Glass wool is ineffective when its structure is too fine. Moreover, it causes skin irritation like glass fibres. It is no longer used because of its limited use and because alternative synthetic products are available.

Rock wool
Like glass wool, rock wool is also a voluminous product. Its fine structure and the consequent problems limited its use to a very brief period only.
Polyamide string
Polyamide string wound in the valleys of the corrugations where the perforations are located can be considered as the prototype of synthetic envelopes. Although effective to prevent soil invasion, it has not been accepted because of its fine structure with the accompanying risk of blocking and clogging.

Loose polypropylene fibres: pre-wrapped loose material (PLM)
The wrapping of drainpipes with loose polypropylene fibres came into being as an alternative to organic coconut fibre wrapping, which have a limited lifetime. Polypropylene fibres virtually do not decay once installed in the soil, so they have more or less an unlimited life. The characteristic opening size of these envelopes can be adapted to that of the surrounding soil in which they lie by varying the diameter of the fibres. Envelopes of polypropylene can consist completely of finer fibres which are a waste product of the carpet industry, or new coarse fibres, or a blend of the two. The finer fibre wrappings have an O₉₀ of about 200 to 350 µm, the coarse fibre wrappings have an O₉₀ of 700 to 1000 µm, and the blended wrappings have an O₉₀ of 350 to 700 µm. Although the finer fibre wrappings carry a potential risk of blocking and clogging, no justifiable complaints have been noted. Practical experience confirms the superiority of the coarser fibre wrappings (O₉₀ ≥ 350 µm) with a limited soil invasion under normal drainage circumstances. The materials are used extensively in the Netherlands. Guidelines for design, construction, quality control and inspection have been prepared (NEN 7090, KIWA staff 1992a and b). Looser fibres are considered voluminous and increase the effective drain diameter.

Geotextiles
Drains can be wrapped with woven and non-woven geotextiles, but as they can be made with thin and fine materials, the risk of clogging and blocking and consequently of a reduced drainage performance is high. Although thin, coarser materials can be considered, they do not have the advantage of voluminous materials and the risk of soil invasion limits the use of geotextiles as drain envelope materials. Some research and field experiments even suggest that it is likely that thin, finer geotextiles may hamper drainage performance, but there is no clear evidence of this as yet and on the whole they perform quite well. Below are a number of field studies with information relevant to the application of drains in agricultural settings.

Case study 1. One of the most recent studies reported, and probably a landmark for details on long- and short-term behaviour of synthetics in relation to drainage applications is the study that was executed by the Federal Highway Administration (Koerner 1994, Koerner et al. 1996, and Wilson-Fahmy et al. 1996). The study reports on the results of exhuming 91 sites in 17 states throughout the United States that were in use for between 1 and 15 years,
though age did not seem to affect the results. About 75% of the sites were in hot and cold humid areas, and 25% in dry hot climates. Typical drainage conditions investigated are shown in Figure 87 from which it is clear that few of them relate to agricultural applications of subsurface drains, however the behaviour of the geotextiles used will be indicative of what to expected under agricultural conditions. Each application consisted of three components: the filter, the drain and the system, and each was judged on its performance. The system as a whole functioned when all three components performed satisfactorily. Failure was related to construction and/or maintenance problems, to clogging of the drainage medium by sediment, and to failure of the geotextile to retain the soil (filter working).

With respect to the drainage medium, improper product use, excessive deformation of the core of geocomposites, and installation damage were reported in a few cases. A major finding was that 8 of the 10/41 geocomposite sites failed as a result of retention problems. Soil finer than the openings moved into the drainage core and completely clogged it. AOS of the fabric was 0.21 mm (no 70 sieve) while soil particles in the core were less than 0.15 mm. No further details are given, except that it was observed that backfill was improper, resulting in large voids from which suspended particles moved freely into the drain core through the fabric, probably under dynamic load. It was concluded that good contact between geotextile and base soil right from the start is important to it to be a success. Because this type of failure was deemed installation-related the 8 cases were not considered in the comparison of ground truth and design criteria (Table 36).

The types of problems encountered with the filters were excessive soil clogging; slag precipitation, inadequate strength (geotextile and seam), excessive UV degradation; and, the earlier mentioned inadequate soil retention (clogging of drainage core). Wilson-Fahmy et al. (1996) compare existing permeability, retention and excessive clogging criteria for geotextile filters with the results of the study (Table 36). They classified the soils as granular, mixed and fine, according to the Unified Soil Classification System. The significance of this division is not made entirely clear, except that it divides soils in certain classes. In agriculture all three types might be encountered. Regarding the permeability criteria it is noted that Giroud (1982) and FHwA criteria (Christopher and Holtz 1989) are preferable in correlating their predictive behaviour with the field sites. For retention criteria, Task Force 25, FHwA (steady flow, 1989), Ogink (1975), CFGG (1986) and Carroll (1983) all give good results. With regard to excessive clogging criteria it was observed that none were applicable, nor where they needed for granular soils. For mixed soils most were also not applicable, while for fine soils the FHwA criterion seemed most appropriate. Wilson-Fahmy et al. (1996) recommend for all three criteria the most recent FHwA guidelines (Christopher and Holtz 1992).
Case study 2. In 1976 in the Central Valley of California, a field experiment was established using three different types of synthetic envelope materials, including a bulky fibre envelope made of carpet waste material from the Soviet Union. A gravel envelope was used as a control. All of the envelopes performed satisfactorily, but the gravel envelope produced much higher rates of drainage than any of the synthetic envelopes. The difference was attributed to the larger effective diameter of the gravel envelope which improved the hydraulic function of the drains (Johnston, 1978, 1981).

Miscellaneous case studies. Major sources of recent experiences with synthetic materials are the Fourth and Fifth International Conference on
Geotextiles, Geomembranes and Related Products (Hoedt 1990, Karunaratne et al. 1994), and the ASTM sponsored symposium in Denver Colorado (Bhatia and Suits 1996) on recent developments in geotextiles and prefabricated drainage geocomposites. Case study 1 came from the latter source. Numerous articles are available for perusal but few are directly related to the application of drain envelope for agricultural soils and conditions.

Table 36 Results of testing highway drains that use geotextiles. (after Wilson-Fahmy 1996).

<table>
<thead>
<tr>
<th>Source</th>
<th>Part in Table 35</th>
<th>Granular Soil</th>
<th>Mixed Soil</th>
<th>Fine Soil</th>
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<tr>
<td></td>
<td>Agree</td>
<td>Disagree</td>
<td>Agree</td>
<td>Disagree</td>
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</table>
| a  
  Permeability criteria | Giroud (1982) | I 15 | 1 | 44 | 2 | 10 | 1 |
|                         | CFGG (French 1) | M 0 | 9 | 0 | 3 | n/a | n/a |
|                         | CFGG (French 2) | M 0 | 15 | 25 | 21 | 19 | 1 |
|                         | CFGG (French 3) | M 0 | 7 | 6 | 37 | 15 | 5 |
|                         | FHwA - not critical, not severe (1989) | not | 14 | 2 | 44 | 2 | 19 | 1 |
|                         | FHwA - critical, severe (1989) | not | 7 | 9 | 43 | 3 | 19 | 1 |
| b  
  Soil retention criteria | Zitscher (1974) | C n/a | n/a | 37 | 3 | 12 | 7 |
|                         | Ogink (1975) | B 16 | 0 | 38 | 2 | 19 | 0 |
|                         | Sweetland (1977) | E 16 | 0 | 12 | 28 | 0 | 19 |
|                         | Schober and Teindl (1979) | G 16 | 0 | 36 | 4 | 9 | 10 |
|                         | ICI Fibres (= Rankilor 1981) | F 16 | 0 | 12 | 28 | 2 | 17 |
|                         | Giroud (1982) | I 14 | 1 | n/a | n/a | n/a | n/a |
|                         | Carroll (1983) | J 16 | 0 | 38 | 2 | 19 | 0 |
|                         | CFGG (1986) | M 16 | 0 | 38 | 2 | 19 | 0 |
|                         | AASHTO (1986) | T 16 | 0 | 38 | 2 | 18 | 1 |
|                         | FHwA steady flow (Christopher and Holtz 1989) | not | 16 | 0 | 38 | 2 | 19 | 0 |
|                         | FHwA dynamic flow (Christopher and Holtz 1989) | not | 7 | 9 | 1 | 39 | 16 | 3 |
|                         | Fischer et al. (1990) | O 16 | 0 | 30 | 10 | 1 | 8 |
|                         | Luettich et al. (1992) steady flow not | 16 | 0 | 35 | 5 | 16 | 3 |
|                         | Luettich et al. (1992) dynamic flow not | 15 | 1 | 34 | 6 | 1 | 18 |
| c  
  Excessive Clogging | CFGG (1986) | M n/a | n/a | 24 | 22 | 19 | 1 |
|                         | FHwA (1989, Christopher and Holtz 1989) | not | n/a | n/a | 33 | 13 | 19 | 1 |
|                         | Fisher et al. (1990) | O n/a | n/a | 28 | 18 | 19 | 1 |