HR Wallingford

PERMEABLE PAVEMENTS

by

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ABSTRACT

A literature search, funded by the Department of the Environment, was made which reviewed the available literature concerning the structural and hydrological characteristics of different types of permeable pavement.

New commercial, industrial or residential developments in a catchment have the effect of increasing the volume and rate of storm run-off and can overload the existing sewerage system. Provision of new interceptor sewers and extra treatment capacity is very costly. A developer may therefore be required to restrict the rate of run-off entering an existing public sewer from the new site. This can be achieved by the use of detention tanks within the site but these can again be costly and may occupy valuable land.

A potentially better solution is the use of permeable pavements for large areas such as car parks; the volume of run-off is reduced and the peak flows are delayed and attenuated. Another advantage of this type of system is that it can improve water quality by filtering pollutant particles in the run-off.

If the use of permeable pavements increases due to their economic advantages, it will be necessary to take account of the changed run-off characteristics when designing or simulating the performance of storm sewerage systems.

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1. INTRODUCTION

New commercial, industrial or residential developments in a catchment have the effect of increasing the volume and rate of storm run-off and can overload the existing sewerage system. Provision of new interceptor sewers and extra treatment capacity is very costly. A developer may therefore be required to restrict the rate of run-off entering an existing public sewer from the new site. This can be achieved by the use of detention tanks within the site but these can again be costly and may occupy valuable land. A potentially better solution is the use of permeable pavements for large areas such as car parks; the volume of run-off is reduced and the peak flows are delayed and attenuated. Another advantage of this type of system is that it can improve water quality by filtering pollutant particles in the run-off.

If the use of permeable pavements increases due to their economic advantages, it will be necessary to take account of the changed run-off characteristics when designing or simulating the performance of storm sewerage systems.

2. BACKGROUND

A research proposal on the Scope for Control of Urban Runoff was developed by the Construction Industry Research and Information Association (CIRIA) in 1987 in conjunction with its members in order to promote, where appropriate, increased control of urban runoff.

The resulting study carried out in 1989 (3) acknowledged that there was an appropriate level of control of runoff within the catchment, whether within the curtilage of the individual property, the development site, the urban sub-catchment or the overall river catchment.

Existing practice, procedure and legislation in England and Wales for urban runoff control and management was reviewed. The study also reported on findings and recommendations for drainage, sewerage and catchment flood control.

The study concluded in its guidelines that porous pavements could provide a valuable addition to the available methods for control of run-off and it recommended that further research be carried out into their long term performance.

3. SCOPE OF REPORT

This report is intended to review the available literature concerning permeable pavements, identify the types of permeable pavement used in the construction industry and analyse the existing data about their hydraulic characteristics. It is not proposed to investigate pervious surfacings laid on top of impermeable asphalt bases, such as used in road construction as a means of reducing splash and spray.

4. DESCRIPTION OF A PERMEABLE PAVEMENT

Diniz (8) described a permeable or porous pavement as composed of four layers:

a) minimally compacted sub-base consisting of undisturbed existing soil or, in the case of unsuitable base soils, an imported and prepared base course. Auxiliary drainage structures may also be required.

b) reservoir base course consisting of 25.4mm to 50.8mm diameter crushed stone aggregate. The thickness of this layer is determined from runoff storage needs and frost depth considerations.

c) 50.8mm of 12.7mm crushed stone aggregate to stabilize the reservoir base course surface.

d) Porous asphalt concrete surface course whose thickness is based on bearing strength and pavement design requirements.

A typical section is shown in Figure 1.

Developments and modifications of the concept of the permeable pavement tend to be built round the above structure; with either modifications to the material forming the surface course; inclusion of geotextile between the surface course and the stabilizing layer; inclusion of a geotextile or impermeable membrane between the reservoir base course and the sub-base or the addition of supplementary drainage structures to the sub-base.

5. TYPES OF PERMEABLE PAVEMENT

The literature search has revealed four main types of surface associated with permeable pavements:

a. Concrete grid paving

Concrete grid or lattice block paving is formed from either reinforced precast concrete units, hydraulically pressed precast concrete units or concrete cast in situ around formers with the concrete being reinforced with steel mesh.

Grasscrete (R), Grasscel (R) and Grassgrid (R) are examples of some of the concrete porous pavement blocks manufactured in the British Isles, see Appendix 1.

Day et al (6) give a brief historical resume of concrete grid pavements before describing the three types of grid marketed in the United States of America, see Figure 2. These are categorized as lattice pavers, castellated pavers and poured-in-place pavers where

"Lattice pavers have a flat grid-like configuration. Castellated pavers are characterized by raised battlements or sections above the major portion of the exposed upper surface. Both lattice and castellated pavers are moulded in a fashion similar to concrete blocks and range in surface area from 2 to 4 square feet. With poured-in-place pavements, the concrete is poured over plastic forms containing steel reinforcing bars".

In the latter case the form is removed by burning after the concrete has set and the voids filled with topsoil and grass seed.

Pratt and Mantle (32) describe a porous block pavement experimental site on the Clifton campus of Trent Polytechnic.

"The pavement is surfaced with concrete block paving, ..., such that rainwater may infiltrate the surface into the sub-base. The paving blocks have a pattern of holes from the surface to the bedding layer and a pattern of raised discs between the holes on the surface to carry vehicle tyre loadings. The holes are gravel- filled, and the raised discs prevent the gravel and any accumulation of silts being compacted, so limiting the infiltration of stormwater. The use of the permeable block paving over the entire parking surface eliminates the requirement for traditional grading of the surface toward gully inlets", see Figure 3.

In describing the role of Grasscrete ®, a cast-in-situ form of pavement, Walker (52) states that

"the porous paving was originally designed as an attractive load bearing surface for car parks, access road and embankments having the general appearance of grass and the load bearing and anti-erosion characteristics of reinforced concrete".

and went on to add that the

"system offers significant benefits in reducing runoff from car parks, contributing to subterranean water table re-charge, reducing the rate of evaporation of ground water in hot climates and offers advantages over solid concrete surfaces for flood alleviation and land drainage channels in difficult soil conditions".

b. Porous asphalt

The majority of permeable pavements described in references accessed during the literature search have been constructed from porous asphalt.

Diniz (7) described most porous pavements as being

"constructed as a layer of open graded asphalt concrete underlain by a gravel base course with an appreciable storage capacity. The whole system may be isolated from the natural ground by an impermeable membrane such as a polyethylene liner, in which case some type of artificial drain would be needed. Or the porous pavement system may be allowed to drain into the natural ground at all points of contact. The latter does not preclude the use of artificial drains, as in the case of highly impervious natural ground".

Diniz also noted that

"Porous pavements provide design storage so that they may be used to reduce run-off to pre-urbanization levels, but, more importantly, they can be used to capture the initial run-off or "first flush" volume which most studies indicate to be the most degraded in terms of pollutant concentrations. The high pollutant concentrations in the initial run-off are reduced by dilution with subsequent flows which are less polluted".

Similarly relating to the drainage of the pavement, Field et al (10) stated that

"Water can be stored in the crushed stone base until it can percolate into the sub-base or drain laterally".

Referring to the surface characteristics, Thelen et al (46) commented that

"The recommended surface thickness to provide permeability, strength, flow and durability is 4 inches, with the reservoir capacity of the surface and base courses being based on 15% and 30% air voids respectively".

Adaptations of the principle of the porous asphalt surface are described by Hogland et al (19) and Niemczynowicz et al (30) as the unit superstructure which "consists of a pervious surface, open aggregate and a geotextile in which rain and surface water are distributed by means of infiltration to the underlying soil", see Figure 4.

Ichikawa and Harada (22) refer to the pavement as drainage infiltration strata which is

"an artificial soil structure composed of a permeable pavement, a gravel layer, a sand layer and a drainage pipe with an impermeable membrane. The surface of the infiltration strata is covered by an artificial turf".

whereas Minigawa (28) and Wada et al (50, 51) refer to the structure as a storm water infiltration system

"composed of permeable pavements, permeable connection boxes, permeable underground pipes and permeable 'U' shaped trenches", see Figure 5.

with Raimbault (38) including

"gulleys with longitudinal drains, sand traps, longitudinal and transverse trenches".

as reservoir structures in association with the porous pavement.

c. Concrete block or Set paving

Block or set paved surfaces consist of shaped concrete blocks, granite sets, flagstones or bricks laid on a bed of sand over a sub-base of aggregate, see Figure 6.

Concrete block paving is generally considered to be virtually impermeable and made up of high quality concrete blocks on a laying course of screeded sand.

Clark (4), however, showed concrete block pavements to be initially permeable although he went on to add that the

"block paving eventually becomes sealed with materials such as detritus, oil and rubber".

van de Ven and Zuidema (48), reported on the infiltration associated with the laying of bricks over a sandy base, and Leenders (26) investigated the infiltration characteristics of rectangular concrete blocks laid over sub-bases of incinerator ashes, broken concrete and masonry, and sand in Holland.

whilst

Jacobsen and Harremoes (25) described the runoff attenuation from a pavement constructed from granite sets in Denmark.

General overviews of the types of permeable pavements used for storm water management and the countries in which they are employed are provided by Hogland (16), Pratt and Hogland (33) and Pratt (37).

6. INFILTRATION AND RUN-OFF CHARACTERISTICS OF PERMEABLE PAVEMENTS

The primary benefit of a permeable pavement is an appreciable reduction of the runoff rate and volume from impervious urban areas. If adequately designed all of this runoff may be captured, detained and release at a slower rate to prevent increases in flood flow.

Ichikawa and Harada (22) defined the dynamics of a drainage infiltration strata in three stages:

a) the infiltration of all the stormwater through the permeable pavement.

b) the retention of the infiltrated water within the gravel layer beneath the permeable pavement, with a time lag between the beginning of the rainfall and subsequent drainage. Upon commencement of drainage the difference between the cumulative volumes of rainfall and drainage represents the retention within the subbase.

c) reduction of retention volume and drainage by evaporation after cessation of rainfall.

The process is illustrated in Figure 7 where the cumulative volume of infiltration is assumed to be equal to the rainfall volume.

Goforth et al (12) describe field and laboratory experiments in the city of Austin, Texas. The infiltration and runoff from three parking lots with porous surfaces were compared with similar conditions for two parking lots with impervious surfaces.

Stormwater runoff conditions were generated for porous asphalt, lattice block, gravel trench, asphalt and concrete lots. Simulated rainfall intensities ranged from 12.7mm/hr to 42.4mm/hr.

For the porous asphalt lot a maximum intensity of 42mm/hr was achieved with no resulting surface runoff. In all cases the detention time was constant at 42 minutes. The average observed base runoff neglecting measurement error was 50%.

The runoff from the lattice block lot amounted to 26% of the rainfall, showing a higher retention rate than the porous asphalt lot. However, the detention time was only 11 minutes. This rapid response was indicative of the fact that the water which does not percolate the base layer is transported off the lot within a duration similar to impervious surfaces.

The short detention time also reflected the non-uniform permeability of the surface layer. The lattice block construction allowed an initial portion of the rainfall volume to be stored in the depressions and sand within the surface interstices before overland flow began. Non-uniform surface impermeabilities along with some areas of underlying and adjacent clay soils resulted in a minimal amount of water lost through infiltration and lateral discharge.

Subsurface flow from the gravel trench lot amounted to 73% of the input rainfall with an average detention time of 24 minutes.

Testing with conventional surfaces constructed of impervious asphalt and concrete showed average runoff values of 71% and 46% when compared with the input rainfall. Detention times averaged 3 minutes and 16 minutes respectively.

In comparison and complementary to the work undertaken by Goforth et al in Texas, Hogland et al (19) studied the infiltration capacities of car parks constructed using the unit superstructure. The infiltration and runoff were monitored from the car park associated with a shopping centre and school, which had been in use for 4.5 years before measurements were made, and a car park heavily utilised by vehicles associated with construction work on a nearby building site. The construction site car park was surfaced with two types of porous asphalt, HABD-12 ® and DRAINOR ®.

The 4.5 year old unit superstructure had an average infiltration capacity of 65mm/minute with a maximum capacity of 200mm/minute. The lowest value of infiltration capacity was less than 1mm/minute, equivalent to the capacity of a permanent lawn and found adjacent to grassed areas where runoff spread onto the unit superstructure.

The HABD-12 suffered a severe reduction in infiltration capacity due to the clogging of the surface by clay spread over the surface during construction work. Infiltration capacity on the heavily used surface reduced to less than 1mm/minute with consequent runoff. On areas less exposed to construction work the capacity was 10mm/minute increasing to 30mm/minute at the edges of the unit superstructure, a capacity sufficient to prevent runoff.

After the completion of the construction work the HABD-12 surface was replaced with DRAINOR. Tests on the DRAINOR pervious surface showed it to have an infiltration capacity of 420mm/minute.

Murphy et al (29) assessed various methods that could be adopted to alleviate the problems associated with stormwater runoff and its effect upon water quality in receiving waters for the City of Rochester, New York. Porous pavements were studied at two sites, with investigations into the hydrology and the permeability of the pavement. Data from the hydrological investigation site were compared with data from a control surface constructed of impervious asphalt at the same site. The pavement consisted of a 5in. surface layer of porous asphalt overlying a 9in. stone base.

Peak runoff rates from the porous pavement were significantly lower than those recorded from the impervious surface, with an average reduction of 76%, see Table 1. Figure 8 illustrates the runoff hydrographs recorded for one storm event and graphically shows both the reduced runoff, time lag and extended hydrograph profile associated with porous pavements when compared to conventional surfaces.

Permeability tests undertaken on cores from the sites illustrated the reduced permeability with time due to clogging, but more specifically the reduction in permeability between surfaces subject to minimal passage of vehicles and those with higher traffic densities. During the period of site monitoring from September 1979 to August 1980 the lightly trafficked site permeability reduced from 1980in/hr to 540in/hr. Permeabilities from the more heavily used site varied between 170in/hr to 43in/hr in 1979 for cores taken from clean and dirty areas, these values reduced to 160in/hr and 27in/hr after a years use. Further permeability testing was undertaken to simulate the gritting of surfaces that occur in winter. Initial application of the sand caused a marked reduction in the permeability from a value of 420in/hr but with successive applications of sand the permeability rate stabilized at 27in/hr, see Figure 9.

Ichikawa and Harada (22) reporting on observations over a six year period from a drainage infiltration strata built on a baseball field at Tokyo University noted that base runoff varied between 25% and 55% of the input rainfall with the residue assumed to be retained within the strata or lost through evaporation. Detention times ranged between 1 and 10 hours with a peak runoff of less than 5mm/hour. The low value of peak runoff at 30-50% of the design value was considered to be due to the clogging of the drainage pipe by sand.

Urban and Gburek (47), and Gburek and Urban (11) describe an experimental facility constructed at Willow Grove, Pennsylvania to investigate the feasibility of using porous asphalt for in- situ stormwater detention and groundwater recharge. Storms monitored during June 1978 and July 1979 produced no surface runoff from the porous asphalt surface whilst showing a groundwater recharge amounting to between 70% and 90% of the incident rainfall.

Minagawa (28) monitored three storm water infiltration systems constructed in Tokyo between 1981 and 1986 to assess the effect of the systems on surface runoff control. The systems were comprised of permeable pavement, permeable underground pipe, permeable trench, detention basins and conventional sewage pipes.

The average runoff from the infiltration system ranged between 0% and 5.4% of the surface rainfall whereas the runoff from an adjacent impermeable surface was 59% of the rainfall volume, see Table 2.

The infiltration capacities of the permeable connection boxes and permeable pavement reduced on average by 80% between 1981 and 1986, however, the infiltration capacity of the underground pipes was unaffected during the same period. The infiltration capacity of the connection boxes was restored after removal of sediment build up and the porous pavement infiltration capacity restored after cleaning the surface with a water jet.

Pratt et al (35) found that the initial loss due to surface wetting, depression storage was greater on the concrete grid type of porous pavement compared to a conventional impervious surface, typically 4mm to 6mm as compared to 1mm.

Runoff from the porous pavement was found to be of the order of 30% to 50% of the total rainfall within the duration of the storm whereas impermeable surfaces commonly discharge almost all runoff within the storm duration.

During a 30 day rainfall simulation the percentage runoff for the four types of sub-base tested, ie blast furnace slag, limestone, gravel and granite, the respective runoffs were 55%, 61%, 63% and 75%. The differences of runoff was thought to be possibly associated with the characteristics of the four stone types, as they varied in surface, point contact density and absorption characteristics.

Tests with the pavement with the limestone sub-base showed that after 9 days without rainfall, the initial loss before runoff for the succedding storm was 9.5mm. Only 16% rainfall was discharged within the storm duration, and only a further 27% of the total rainfall ever flowed from the construction.

The difference between total rainfall and the total discharges was the water held long-term in the construction, which wholly or in part evaporated before the next storm event.

Day et al (6) describe runoff tests undertaken on three types of concrete grid pavement and the comparison of the results with runoff measured from a concrete slab pavement used as a control in the experiments. Lattice, castellated and cast-in-situ types of concrete grid pavement along with concrete block pavement were subject to rainfall durations between 30 minutes and 120 minutes with rainfall intensities ranging from 0.59in/hr to 3.54in/hr. No runoff was recorded from the lattice or castellated pavements for any of the rainfall events tested. The runoff coefficient for the cast-in-situ pavement averaged 0.005, these results comparing with the average runoff coefficient of 0.78 for the concrete block pavement.

Grass Concrete Limited (13) quote from previous experimental work undertaken by Day (5) on the runoff characteristics of Grasscrete, a cast-in-situ form of concrete grid pavement.

The pavement was subjected to rainfall durations between 30 and 120 minutes and an intensity of 4.15in/hr. Pavement slopes of between 2% and 7% were tested and runoff coefficients ranging between 0.02 and 0.35 were recorded, see Table 3. Day et al (6) noted that with increasing pavement slope that the runoff coefficient increased for both the lattice and castellated types of grid pavement.

Wada and Muira (51) undertook experimental work where simulated rainfall on a permeable pavement and roadside gutter were studied in order to measure the storm water runoff volume. Water was also introduced to one side of a permeable sewer pipe in order to measure the volume permeating the pipe wall. The groundwater level at the experimental site varied between 0.5m and 2.0m below ground level. The rate of runoff per unit of permeable area relative to the initial infiltrated volume varied dependent upon the groundwater level.

The final infiltration capacity of the facility was found not to vary with ground water level relative to the base of the infiltration facility and remained constant between 40mm/hour to 50mm/hour.

Smith (42) studied the drainage and thermal performance of a concrete grid pavement in the City of

Dayton, Ohio. A control surface constructed of asphalt was also monitored. Coefficients of runoff for the grid pavement ranged from 0 to 0.35 with an average of 0.1 compared to 1.0 for the impervious asphalt surface, see Table 4. Higher values of coefficient for the grid pavement tended to be associated with runoff generated under wet antecedent soil moisture conditions.

Radiometric and dry bulb temperature readings from the concrete grid and asphalt gave average radiometric readings respectively of 38 and 43 degrees Celsius and dry bulb readings of 26 and 28 degrees Celsius illustrating the ability of grid pavements to attenuate temperatures as well as surface runoff.

Laboratory experiments by Clark (4) on the infiltration rate associated with concrete block paving subjected to rainfall intensities between 25 mm/hr and 50 mm/hr showed that up to 25% of the rainfall could penetrate to the subgrade, see Figure 10. Simulation of the effect of silt binding the joints between the blocks reduced the infiltration to 1%, see Figure 11.

van de Ven and Zuidema (48) studied the infiltration characteristics of a 0.7 hectare car park in Lelystad, Netherlands. The car park was covered with asphalt and bricks laid on a sandy base. Approximately 70% of surface rainfall infiltrated through the surface. The mean infiltration rate was 13mm/hour with a minima of 6mm/hour and a maxima of 29mm/hour.

Leenders (26) undertook infiltration experiments on a 300m length of road surfaced with concrete blocks in Rotterdam. The road was sub-divided into four units with the sub-base layers comprised of sand, demolition waste, incinerator ash, and cement bonded incinerator ash. Each unit was further split into a section with and without an impermeable membrane below the sub-base layer. The site was monitored between September 1986 and October 1987. During this period the infiltration rates, expressed as a percentage of the rainfall falling on each unit, showed respectively that 25%, 42%, 23% and 13% of the rainfall infiltrated and passed through the sub-bases comprised of the sand, demolition waste, incinerator ash and cement bonded incinerator ash.

Site investigations by Jacobsen and Harremoes (25) of a 682 square metre granite set paved surface at Lyngby in Denmark, for a five month period in 1978, showed the total runoff to be 11% of the total recorded rainfall. The relationships between runoff volume per unit area and rainfall depth for an asphaltic and paving stone surface presented exemplify the invalidity of using the relationship from an impervious surface to represent a semi- pervious surface. The important effect of antecedent rainfall on a semi-pervious surface is also shown by the data, see Figure 12.

7. EFFECT OF PERMEABLE PAVEMENTS ON WATER QUALITY

The CIRIA report (3) noted that in an urban conurbation

"the types and amounts of pollutants are a complex function of atmospheric water quality, the type and intensity of urban land use activity, surface compositions, the type and density of road traffic, and steet cleaning practices".

Permeable pavements are considered capable of enhancing the quality of runoff from urban areas in two ways. Firstly by reducing the runoff volume with the consequent reduction in quantity of pollutants reaching the receiving waters and secondly by modification to the chemical composition of the runoff as it passes through the pavement.

Goforth et al (12) in their study of several pavement types in the City of Austin, Texas noted that during a majority of storm events a first flush effect of suspended solids was experienced on porous pavements, see Table 5. Flow weighted average concentrations of 240 mg/l and 175 mg/l were recorded from the gravel trench and porous asphalt surface compared to 24.5 mg/l from the lattice block surface. These higher concentrations were attributed to erosion of the diversion channels for the porous asphalt surface and the flushing of the fines from the gravel trench.

With the exception of the lattice block pavement these concentrations are higher than concentrations registered from conventional asphalt or concrete pavements.

The chemical oxygen demand for porous pavements show a first flush effect when compared with conventional pavements, however the flow weighted average demands are similar with the exception of the gravel trench which shows a higher demand level.

No significant differences in nitrogen concentrations were recorded between porous and conventional pavements.

Lead and zinc concentrations were similar for the porous and conventional pavements but noticeably higher in both cases for the gravel trench, with the average concentrations of zinc being greater from the pervious than the impervious pavements.

Low concentrations of organic pollutants were found in the lattice block and porous asphalt pavements.

Balades and Chantre (1) compared the pollutants associated with two car parks in the Greater Bordeaux Municipal area in France, one surfaced conventially, the other with permeable pavement.

Lead and suspended matter concentrations recorded from the permeable surface were respectively 7.3% and 50.8% of the corresponding pollutant values recorded from the conventially surfaced car park. The chemical oxygen demand for the permeable surface was found to be 11.9% of the demand for the conventional surface, see Table 6.

Hogland et al (17, 19) investigated the pollution due to snowmelt and traffic on the unit superstructure. Concentrations of suspended solids, total solids and metals in the snow were measured prior to snowmelt and then measured in the runoff through the unit superstructure.

Reductions in the concentrations of suspended solids, total solids and metals was noted, see Table 7. However, increases in nitrogen and chloride were noted, a possible explanation being the presence of nutrients producing the nitrogen and chloride both in the surrounding agricultural soil or even present in the asphalt.

The greatest concentration of pollutants in the unit superstructure was found in the geotextile layer with the lowest concentrations in the aggregate layer sandwiched between the porous asphalt and the geotextile layer, see Figure 13.

The chemical composition of the water passing through the unit superstructure remained unchanged as it passed through the unit.

Further studies by Hogland (16), Hogland and Spangberg (20) of the unit superstructure in the laboratory were conducted simulating rainfall durations of between 1.5 and 30 years of precipitation. The concentrations of pollutants were highest on the geotextile surface for the majority of constituents. No increase in pollutant concentration could be found in the soil under the geotextile even after a simulated period of 30 years rainfall.

Pratt et al (35, 36) studied a porous pavement underlaid by a gravel layer and four types of unbound sub-base aggregate under laboratory and field conditions.

Initially after field construction of the castellated grid pavements the concentration of suspended solids discharged from the sub-base was 100mg/litre. After the washing out of fines from the sub-base material this concentration reduced to 40mg/litre. These values compare with concentrations from impermeable surfaces ranging from 30mg/litre to 300mg/litre with measured values of 1000mg/litre having been recorded.

Lead concentration in the runoff from the porous pavement sub-base was consistent at 0.06mg/litre with over 80% of the lead being retained in the gravel layer, a comparable figure for the organic pollutants also being retained in the gravel layer.

The range of water quality discharges from the sub-base were dependent upon the type of stone forming the sub-base. In each case the suspended solids concentration was limited to a range from 0mg/litre to 50mg/litre.

The porous pavement showed greater stability in the effluent discharge quality in both value and range of pollutant concentrations over the short and long term when compared to impervious pavements.

Day et al (6) in their study of runoff from concrete grid pavements also investigated the pollution abatement characteristics. Runoff was only monitored from the cast-in-situ block and the concrete slab pavements, no runoff being registered from the lattice or castellated pavements, see Table 8. The pollutant concentrations in the runoff were normalized by reference to the rainfall pollutant concentrations to allow comparison between tests. The report concluded that the pollutant concentrations in the runoff from the cast-in-situ pavement were greater than the corresponding ones from the concrete slab except for organic phosphorus, lead, zinc and chromium. This tendency to higher pollutant concentrations was attributed to the grass and soil within the voids of the block provided an environment whereby microorganisms and macroscopic fauna could live and metabolize.

Analysis of the percolate from the Willow Grove porous asphalt pavement, Gburek and urban (11), showed the chemical composition to have changed little from the incident rainfall. The main effect on water quality waas a shift in pH value from acidic rainfall to neutral percolate.

8. CLOGGING AND THE MAINTENANCE OF INFILTRATION CAPACITY

In order to ensure the efficient operation of a permeable pavement as a design for reducing urban runoff, and a method of improving water quality, then the infiltration capacity of the system must be maintained.

Balades and Chantre (1) reporting on trials in the Greater Bordeaux Municipal area found that only surface clogging of the porous pavement occurred. This clogging could be remedied by regular cleaning of the surface by suction sweeping, cleaning by using a high pressure water jet or ultimately planing the clogged coating and relaying a new layer of porous material.

Diniz (8) considered that in order to minimise clogging that

"all ground preparation and earth work should be finished prior to installation of porous pavements. After construction, the haulage of clogable materials across porous pavements must be conducted with extreme care to prevent spills".

Investigations at the Woodlands construction site, north of Houston, in Texas showed that if a spill occurred, that immediate vacuuming and washing with a water jet would restore pavement permeability almost to pre-spill rates. Permeability tests at the site indicated a recovery in excess of 95%, though if the pores in the pavement were clogged and the dirt compacted to a depth greater than 0.5 inches, full permeability could not be restored.

Field et al (10) also suggested that

"erosion of surrounding soils cleared especially during construction should be alleviated".

and that

"clogged pavement can be cleared by flushing, and other street cleaning devices such as vacuums and brooms".

Hogland et al (18, 19) relating to the unit superstructure whilst building work was in progress considered the surface to be vulnerable, and that it should be protected against the passage of heavy construction vehicles and the consequent clogging. They also identified direct runoff from adjacent permeable green areas as a potential source of serious clogging of the pavement.

Minagawa (28) also observed clogging at the periphery of permeable pavement. The influence of clogging on the infiltration capacity of the pavement was quantified by stating that if more than 50% of the surface became clogged it was necessary to restore the infiltration capacity by cleaning using a water jet.

Stenmark (43) noted the clogging due to dirt from passing construction vehicles. Flushing of the surface with water at 65 bar pressure was found to restore the infiltration into the surface, increasing the capacity by approximately 400%, see Figure 14.

The development by the University of Lund, Sweden of mobile flushing equipment for permeable asphalt surfaces was also reported.

Maintaining the integrity of a porous pavement constructed on soils subject to frost heave in cold climatic conditions was studied at Sundsvall in Sweden by Hogland and Niemczynowicz (18). The Unit Superstructure formed the basis of the investigation. The construction was varied by using different grades of crushed aggregate beneath the pervious asphalt surface course, with, in one case isolation cellblocks being laid on gravel over the unit superstructure.

Minimum frost heave was experienced with the latter structure.

The majority of the above examples relate to pavement surfaces constructed from porous asphalt. Referring to permeable concrete block paving Pratt et al (35) considered that

"failure of the permeable concrete block paving to infiltrate stormwater would be the result of general filling of the gravel bedding and inlet holes until sediment was caused to be stored on the surface".

Restoration of the surface would involve

"the lifting of the concrete blocks .... the removal of the bedding gravel and the geotextile layer for safe tipping in view of their pollutant content; and the placement of new geotextile, new gravel and the block paving over the original sub-base structure".

The lifespan of a surface was assessed at 15 years before it was considered remedial work would be necessary.

9. COMPUTATIONAL MODELLING OF PERMEABLE PAVEMENTS

The literature search revealed several studies including detailed information on the hydraulic performance of permeable surfaces with permeable and impermeable underlayers.

Jackson and Ragan (24) set up a mathematical model to study the hydraulic behaviour of a porous pavement above an open graded basecourse and an impervious membrane at the level of transverse subdrains. Assumed permeabilities ranged from 1.6in/min to 333in/min, porosities from 13% to 40% and spacing between subdrains from 60ft to 360ft. The Boussinesq equation was used to model the behaviour of the subsurface reservoir, and the water volume retained in storage was computed from the change in the surface of the saturation zone. Design storms for Washington DC were used.

From the results of the deterministic model, multi-variate correlations were obtained to give

$$Q_p = \frac{2\sum P}{n_e} \exp\left(-11.199 + 0.499 \ln(k)\right) \qquad (1)$$

where

Q_p is the flow in ft 3/s per foot of drain.

k is the permeability in in/mm.

P is the rainfall in inches.

and

n is the proportional porosity.

The time taken to drain 50% of the stored volume varied from about 100 minutes to 10000 minutes. For example 50% of the water volume stored in a 360ft * 200ft parking area served by one subdrain beneath 8.2in of material with a permeability of 200in/min (or 13in of material with a permeability of 100in/min) was drained in about 12 hours.

Jackson and Ragan considered that their work showed the feasibility of semi-permeable pavements for car parks and slightly trafficked roads. Their work includes equations and graphical design aids for environmental conditions similar to Washington DC.

Tamai et al (44) in developing a mathematical model to predict runoff for pervious pavements considered that the water flow in the unsaturated and saturated zones of a pavement was continuous. Consequently they treated both zones as one system. Above the phreatic surface where the soil is still saturated but under negative pressure, the permeability was assumed to be equal to that of the saturated region.

The unsaturated infiltration was explained using differential equations formulated by Richards (39). The Richards equation expressed in terms of pressure potential for an incompressible fluid is expressed as follows

$$c(\Psi)\,\frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial y}\left(k_y\,\frac{\partial \Psi}{\partial y}\right) + \frac{\partial}{\partial z}\left[k_z\left(\frac{\partial \Psi}{\partial z} + 1\right)\right] \qquad (2)$$

where

Ψ is the pressure potential.

y the horizontal coordinate.

z the vertical coordinate taken upward.

t time.

k_y hydraulic permeability in the y direction.

k_z hydraulic permeability in the z direction.

$$c(\Psi) = \frac{\partial \Theta}{\partial \Psi} \qquad (3)$$

Θ the moisture content.

Campbell (2) assumed an empirical relationship between the pressure potential Ψ and the moisture content Θ.

$$\Psi = \Psi_e \, (\Theta/\Theta s)^{-b} \tag{4}$$

where

Ψ_e is an air entry potential.

Θs the saturated moisture content.

b is a constant.

The k-Ψ relationship contained in the hydraulic permeability parameter for saturated seepage k_s is derived from

$$k = k_s \, (\Psi_s/\Psi)^{2+2/b} \tag{5}$$

with the permeability of the medium considered to be isotropic, ie.

$$k_y = k_z = k. \tag{6}$$

At the ground surface the rainfall or evaporation is represented by

$$\partial\Psi/\partial_2 = R/k(\Psi) - 1 \tag{7}$$

where

R is the flux across the upper boundary, either positive or negative dependent upon either infiltration or evaporation.

At the surface of a drainage pipe the pressure is assumed to be atmospheric with drainage occuring only if the pressure head in the vicinity of the drain pipe exceeds the atmospheric pressure. Initially no flow is assumed through the drain pipe and consequently along a vertical

$$\Psi + z = \text{constant} \tag{8}$$

at

$$t = 0$$

The Alternating Direction Implicit method was used to solve the equation numerically.

Similarly Ichikawa and Harada (22) used the two dimensional Richards equation to represent the interaction between stormwater and the model strata simulating the drainage infiltration strata.

The following assumptions are made :

- the initial pressure distribution is both uniform and continuous through the model strata.

- the hysteresis effect on the relation between the hydraulic conductivity and negative pressure is not significant through the layers of strata.

- the soil water flow is isotropic for two directions through the layers of the strata.

The relationship between negative pressure and water content of the strata through time is given by

$$C(\Psi)\frac{\partial\Psi}{\partial t} = \frac{\partial}{\partial y}\left(K(\Psi)\frac{\partial\Psi}{\partial y}\right) + \frac{\partial}{\partial z}\left(K(\Psi)\left(\frac{\partial\Psi}{\partial z} + 1\right)\right) \tag{9}$$

the relation between negative pressure and water content by

$$C(\Psi) = -\frac{\Theta s}{\Psi e.b}\left(\frac{\Psi e}{\Psi}\right)^{(1+1/b)} \qquad (10)$$

and the relation between the negative pressure and hydraulic conductivity by

$$k(\Psi) = ks\left(\frac{\Psi e}{\Psi}\right)^{2+2/b} \qquad (11)$$

where

Ψ = negative pressure.

∂z = vertical space increment.

∂t = time increment.

∂y = lateral space increment.

$k(\Psi)$ = relation between negative pressure and hydraulic conductivity.

$C(\Psi)$ = relation between negative pressure and water content.

ks = saturated hydraulic conductivity.

Ψe = air entry value.

Θs = saturated water content.

b = constant.

The conditions used in the computation were

initial condition $\qquad \phi = z + \Psi = \text{constant} \qquad (12)$

upper boundary condition (surface) $R = -k(\Psi)\left(\frac{\partial \Psi}{\partial z} - 1\right)$ (13)

lower boundary condition (drainage pipe) $\frac{\partial q}{\partial z} = K\frac{\partial \Psi}{\partial z} + 1$ (14)

where

R is flux of rainfall.

q is flux of drainage.

k is factor expressing the capacity of the drainage pipe.

Diniz (7,8) developed PORPAV, a computer model used to evaluate the stormwater characteristics of porous and nonporous pavements constructed in the City of Austin, Texas.

A deliberate attempt was made to keep the model as simple as possible and yet to provide adequate quantification of the hydrologic responses of the porous pavement. The model allows a variety of different pavement characteristics to be evaluated, which enables the investigation of various porous pavement systems to be studied especially during the planning phases of a project.

The hydrologic responses of a porous pavement can be simulated by a system of hydraulically connected control volumes for which the inflows and outflows are mathematically defined. The porous pavement, the base and the natural ground (or the drain system) are considered to be sequential but internally independent storage reservoirs.

The basic equation of continuity of conservation of mass is applied to each reservoir

$$\frac{ds}{dt} = I - O \tag{15}$$

where

I = inflow into the reservoir.

O = outflow from the reservoir.

$\frac{ds}{dt}$ = change in storage volume.

The inflow, I, is comprised of direct rainfall onto the porous pavement and the surface runoff hydrograph from contributing areas. The surface runoff is determined using a method determined by Izzard (23) which utilizes a dimensionless hydrograph from paved areas, see Figure 15.

The key parameters are

t_e time to equilibrium.

q_e equilibrium flow.

V_e equilibrium surface detention volume.

i rainfall intensity.

L length of overland flow.

with the following equations defined by the parameters

$$q_e = \frac{w.i.L}{43200} \tag{16}$$

where

q_e = equilibrium flow, cfs.

i = rainfall intensity, inches per hour.

L = length of overland flow, feet.

w = width of overland flow, feet.

and

$$V_e = \frac{k.L^{1.33}\ i^{0.33}}{35.1} \tag{16}$$

where

V_e = equilibrium surface detention volume, cu.ft.

k = an empirically derived, lumped coefficient for the effects of slope and flow retardance of the pavement.

$$t_e = \frac{V_e}{30q_e} \tag{17}$$

t_e = time to equilibrium, minutes.

Using t/t_e values based on the computation interval and Figure 15, the

q/q_e values and the corresponding q values are determined for the rising limb of the hydrograph.

The β factor, defined as

$$\beta = \frac{60q_e.t_a}{V_o} \tag{18}$$

where

t_a = time after rainfall has ceased.

V_o = equivalent to V_e without the rainfall intensity component, in cu.ft.

is used to determine the q/q_e and corresponding q values for the recession limb of the hydrograph.

If the duration of the rainfall is greater than the time required to reach flow equilibrium, ($t_e < t < t_a$), then the q/q_e value remains at a constant value of 0.97 until t_a.

The rainfall hyetograph is input as average intensity per hour for all intervals during which rainfall occurs. Runoff hydrographs are computed for each interval, successively, and summed to determine the cumulative storm hydrograph from contributory areas to the porous pavement.

The inflow hydrograph is converted to units of depth based on the area of porous pavement and computation interval. The rainfall depth on the pavement is summed with the surface runoff depth to determine the total inflow, I, to the porous pavement.

The outflow from the pavement consists of vertical seepage into the pavement, lateral outflow to a drain or into the natural ground, surface runoff from a horizontal pavement, surface runoff from a sloping pavement and volume of water lost to evaporation.

The vertical seepage is determined using the variable head permeability equation as defined by Taylor (45), where

$$K = 2.3 \frac{a.L}{A\ \Delta t} \log \frac{h_1}{h_2} \tag{19}$$

where

K = permeability of flow element, ft/sec.

a = cross sectional area of surface water, sq.ft.

A = cross sectional area of flow element, sq.ft.

L = thickness of flow element, ft.

h_1 = depth of surface water at time t_1, ft.

h_2 = depth of surface water at time $t_2 = t_1 + \Delta t$, ft.

Δt = time interval.

In the porous pavement system, the cross sectional areas of surface water and flow elements are always equal, and so the equation is reduced to

$$K = 2.3 \frac{L}{\Delta t} \log \frac{h_1}{h_2} \tag{20}$$

this equation may be rearranged to solve for h_2

$$h_2 = \frac{h_1}{10^E} \tag{21}$$

where

$$E = \frac{K.\Delta t}{2.3L} \tag{22}$$

the vertical seepage is determined from $h_1 - h_2$

$$\text{Lateral outflow} = S \left(\frac{h_1 - h_2}{\Delta t}\right) P.\Delta t \qquad (23)$$

where

S = storage coefficient of the natural ground.

P = pavement perimeter, ft.

$$\text{Surface runoff from horizontal pavement} = CLH^{1.5} \qquad (24)$$

where

C = input weir coefficient.

L = input weir length, ft.

H = $h - h_0$, ft.

h_0 = depth of dead surface storage on the porous pavement, ft.

h = depth of flow on the porous pavement, ft.

Surface runoff from sloping pavement

$$= y.L.\frac{1.486}{n}\ y^{1.33}\ \ s^{0.5} \qquad (25)$$

where

y = computed depth of flow, ft.

t = width of flow, ft.

n = input roughness coefficient.

s = input energy slope, ft/ft.

Evaporation loss from the surface is determined from

$$E_p = \frac{E_t}{7} \tag{26}$$

where

E_p = peak evaporation rate, in/hr.

E_t = total daily evaporation, in.

$$\text{for } 0 < t_c \leq 6, \qquad E = 0 \tag{27}$$

$$\text{for } 6 < t_c \leq 14, \qquad E = E_p \, \frac{(t_c - 6)}{8} \tag{28}$$

$$\text{for } 14 < t_c \leq 20, \qquad E = E_p \, \frac{(20 - t_c)}{6} \tag{29}$$

$$\text{for } 20 < t_c \leq 24, \qquad E = 0 \tag{30}$$

where

t_c = clock time, hours.

E = instantaneous evaporation rate.

Goforth et al (12) made several modifications to PORPAV.

The vertical seepage previously determined using the variable head permeability equation as defined by Taylor was substituted by the limiting or lower permeability of the conterminous layers as the true indication of the vertical flux of water between the layers, subject to the storage constraints in both layers.

The constant infiltration rate term was replaced by Horton's equation which defines a variable rate of infiltration during and subsequent to a single, continuous precipitation event. The infiltration rate was represented by

$$i_s = i_f + (i_o - i_f)\ e^{-kt} \qquad (31)$$

where

i_s = infiltration rate at time t.

i_f = infiltration capacity (minimum rate) of the soil.

i_o = initial infiltration rate.

k = first order decay coefficient.

t = elapsed time.

The initial infiltration rate is dependent on the initial moisture condition of the soil. Incorporating this expression for the infiltration rate can result in a significantly greater vertical transport calculated during the storm event than by using the constant minimum rate. A constant infiltration rate can be represented by replacing the initial rate by the infiltration capacity of the soil.

Intra-layer flow was represented by a routing procedure to account for the vertical transport of water within the pavement and base layers, simulating the vertical movement of the wetting front through the pavement.

The horizontal discharge was determined using Darcy's law for the flow equation

$$Q_b = K_b A \; dh/dx \tag{32}$$

where

Q_b = average horizontal discharge.

K_b = permeability of the base media.

dh/dx = energy gradient.

A = cross sectional area of flow.

The energy gradient was approximated by

$$dh/dx = H/L$$

where

H = total elevation potential, equal to $d_b + LS_b$

d_b = depth of water in base layer.

S_b = slope of the base layer.

L = normal length of the base layer.

The cross sectional area of the flow was approximated as

$$A = w \; d_b/2 \tag{33}$$

where

w = width of the layer.

This yields

$$Q_b = (K_b w\ S_b)\ d_b/2 + (K_b w)\ d_b^2/2L \tag{34}$$

or on a unit area basis

$$q_b = c_1 d_b + c_2 d_b^2 \tag{35}$$

where

$$c_1 = K_b S_b/2L \tag{36}$$

$$c_2 = K_b/2L^2 \tag{37}$$

Goforth et al go on to state that

"The capacity of the subsurface drain, or in the absence of drain pipes, the transmissivity of the adjacent soil can reduce this lateral discharge rate. By adjusting the pipe size and base layer width, maximum allowable discharge rates can be met. When there is no impermeable boundary present to prevent lateral flux, some horizontal discharge will occur to the adjacent soil. However, this horizontal flux is generally negligible when compared to the vertical component leaving the layer via infiltration because of the much smaller cross sectional area of flow. Also, the moisture content of the surrounding soil increases during the storm event, thereby reducing the energy gradient between the porous media and the soil".

Surface runoff was initially estimated using Manning's equation for runoff from sloping pavements and the broad crested weir formula for flow from horizontal pavements. The weir equation has been replaced by the Manning's equation, with the slope of the energy grade, S, approximated by

$$S = d_s/L \tag{38}$$

where

d_s = depth of water on the surface above the dead storage depth.

Provisions were also made to the programme to allow calculation of the theoretical detention time and a dead storage component.

Wada et al (50) investigating the effect of a permeable stormwater drain in controlling runoff in Kobe City, Japan found that the relationship between the permeabilty and the volume of storm water at the upstream end of the permeable section was

$$\text{Infiltration} = 8.17 * \text{Qup} - 21.15 \tag{39}$$

with a regression coefficient = 0.97

where

Infiltration = permeability in cm/hr.

Qup = volume of storm water at upstream end of permeable section of permeable storm water drain.

Wada and Muira (51) constructed a model to simulate the mechanism of storm water infiltration at combined storm water infiltration facilities. Basic equations to represent unsaturated and saturated pavements were developed based upon experimental work.

The volume of infiltrated stormwater before runoff commences was calculated from

$$F_1 = \frac{R.T_1}{A} \tag{40}$$

where

F_1 = infiltrated volume retained per unit area before runoff commences,mm.

R = volume of rainfall per unit time, l/min.

T = time before runoff commences, min.

A = area of permeable section, m^2.

The final infiltration of the facilities were calculated from

$$F_n = \frac{R - Q_s}{A} * 60 \tag{41}$$

where

F_n = final infiltration capacity, mm/hr.

Q_s = volume of runoff per unit time, l/min.

From the experimental work on the infiltration capacities of the pavements tested it was possible to determine the infiltration velocities of the permeable pavement for both unsaturated and saturated pavements.

These were termed respectively the initial and infinite infiltration velocities.

For the unsaturated pavement the initial infiltration velocity is related to the the rainfall intensity by

$$F = R * A/60 \qquad \text{for } R < S_1 \qquad (42)$$

$$F = S_1 * A/60 \qquad \text{for } R > S_1 \qquad (43)$$

with the rate of change of volume of porewater in the pavement represented by

$$\frac{dV}{dt} = (R - S_1) * A/60 - QT \qquad (44)$$

where

F = infiltration velocity, l/min.

S_1 = initial infiltration velocity, mm/hr.

R = rainfall intensity, mm/hr.

V = total volume of porewater in the permeable pavement, litres

A = area of permeable pavement, m^2.

QT = volume of infiltration water flowing into the infiltration pipe, l/min.

The pavement becomes saturated when the total volume of porewater is equivalent to the total volume of porespace in the pavement.

The infiltration velocity is then determined from the infinite infiltration velocity using

$$F = S_2 * A/60 \tag{45}$$

where

S_2 = infinite infiltration velocity.

If the rainfall intensity exceeds the infinite infiltration velocity then surface runoff commences. The volume of runoff being determined by

$$Q_s = (R - S_2) * A/60 - QT \tag{46}$$

where

Q_s = volume of surface runoff, l/min.

S_2 = infinite infiltration velocity, mm/hr.

Shinoda (41) describes the formula used in the design of infiltration facilities for the City of Fukuoka, Japan. The formula is noteable for the inclusion of a clogging influence coefficient to take account of the reduced infiltration capacity due to blockage by suspended solids.

The unit design capacity of infiltration is represented by

$$q_c = q * c * k_1 * k_2 * k_3 * k_4 \tag{47}$$

where

q_c = unit design capacity of infiltration, l/hr.

q = amount of infiltration capacity in ground, l/hr.

c = safety factor.

k_1 = clogging influence coefficient.

k_2 = groundwater level influence coefficient.

k_3 = rainfall influence coefficient.

k_4 = temperature correction coefficient.

The clogging influence coefficient is calculated from

$$k_1 = e^{-0.015x^a} \tag{48}$$

and

$$a = S_o * \frac{A * f}{L * B} * R_o * T \tag{49}$$

where

S_o = density of suspended solids, kg/m³.

R_o = total annual rainfall, m/year.

$\frac{A * f}{L * B}$ = density ratio of infiltration facility installation.

A = catchment area, m².

f = runoff coefficient.

L * B = bottom area of infiltration facility, m².

T = service life, year.

van de Ven and Zuidema (48) tested five infiltration models to assess their suitability in simulating the infiltration process in the pavement at Lelystad using data from the site in forming the assessment. The model for crusted soils developed by Hillel and Gardner (15), where

$$I = (at + b)^{0.5} - c \tag{50}$$

and a, b and c are parameters of the equation and

I = infiltration in metres
t = time in days.

was considered to provide the best agreement.

Jacobsen and Harremoes (25) included an infiltration capacity formula to represent semi-pervious catchments within the urban surface runoff simulation called URSULA.

The infiltration capacity formula was based on the formulae proposed by Green and Ampt (14) and Mein and Larson (27).

Green and Ampt proposed the equation

$$f_p = K_s[1 + (M_d * S/F)] \tag{51}$$

which was derived by applying Darcy's law to the infiltration from an excess surface water supply from time zero.

where

f_p = infiltration capacity, in/hr or cm/sec.

K_s = saturated conductivity, in/hr or cm/sec.

M_d = initial moisture deficit for the range of content $\Theta_s - \Theta_i$, volume/volume.

S = capillary suction at the wetting front, in. or cm. of water.

F = cumulative infiltration from the beginning of the event, in. or cm.

which gave good agreement when predicting the infiltration capacity for soil profiles that become denser with depth.

Mein and Larson based their computation of vertical flow of soil moisture on the Richards equation which can be written as

$$\frac{\partial \Theta}{\partial t} = - \frac{\partial}{\partial z} \left(K(\Theta) \frac{\partial S(\Theta)}{\partial z} \right) - \frac{\partial K(\Theta)}{\partial z} \tag{52}$$

where

Θ = volumetric moisture content.

t = time.

z = distance below surface.

$S(\Theta)$ = capillary suction.

$K(\Theta)$ = unsaturated conductivity.

The model was developed to represent two stages of soil moisture flow , infiltration prior to runoff and infiltration after runoff begins.

For infiltration prior to runoff

$$F_s = M_d * L_s \tag{53}$$

where

F_s = amount of infiltration up to surface saturation.

L_s = depth of saturated zone, see Figure 16.

In the finite difference form, Darcy's law can be written as

$$q = -K(\Theta)\ (\Phi_2 - \Phi_1)/(z_2 - z_1) \tag{54}$$

where

q = flow rate.

$K(\Theta)$ = capillary conductivity.

Φ = total potential.

z = distance below the surface.

the subscripts 1 and 2 refer to the surface and wetting front.

From Figure 16.

$$z_2 - z_1 = L_s \tag{55}$$

The potential at the surface can be taken as 0, therefore

$$\Phi_2 = - L_s(S_{av} + L_s) \tag{56}$$

where

S_{av} = average capillary suction at the wetting front.

At the moment of surface saturation the infiltration rate is still equal to the rainfall intensity, so that $q = I$.

The capillary conductivity can be assumed to be equal to the saturated conductivity K_s.

Substituting in (54)

$$I = K_s(S_{av} + L_s)/L_s \tag{57}$$

and combining (53) and (57) gives

$$F_s = S_{av} * M_d/[(I/K_s) - 1] \qquad \text{for } I \geq K_s \tag{58}$$

For infiltration after runoff begins

The infiltration rate is now equal to the infiltration capacity, f_p.

and

$$f_p = K_s(S_{av} + L_s + L)/(L_s + L) \tag{59}$$

$$\text{where } L_s = F_s/ M_d \tag{60}$$

and

F = cumulative infiltration at any time

F_s = cumulative infiltration value at moment of surface saturation.

Similarly

$$L = (F - F_s)/M_d \tag{61}$$

hence

$$L_s + L = F/M_d \qquad (62)$$

which gives

$$f_p = K_s[\ 1 + (S_{av} * M_d/F)] \qquad (63)$$

The capillary suction at the moving front is determined from the capillary suction/saturated conductivity relationship for the soil and can be represented by

$$S_{av} = \int_0^1 S.dk_r \qquad (64)$$

where

k_r = relative conductivity

$= K/K_s$

10. SIMULATION OF RUNOFF FROM PERMEABLE PAVEMENTS

The literature search revealed several studies where simulations were undertaken of the runoff from permeable pavements and compared with observed data from the prototype.

Goforth et al (12) simulated the stormwater hydraulics for five types of pavement constructed in the City of Austin, Texas. It is intended only to report on the results from the simulations run on the porous asphalt and lattice block pavements.

Stormwater hydraulics for each pavement type were simulated with a programme called PORPAV, which was calibrated for each type of pavement using one set of observed runoff data. The calibrated coefficients were held constant during the simulation of the remaining events. Pavement characteristics such as pavement length, width, depth and the collection drain capacity were obtained from onsite and construction measurements.

Parameters relating to surface roughness coefficient, volume of dead storage on the pavement and pavement porosity were estimated. The record of observed inflow was input in the programme for each event. Calibration of the model was initialized by varying values of the estimated values to reproduce the observed runoff volume. This was accomplished by adjusting the volume of the base storage for the pervious pavement. The observed peak runoff rate was reproduced by adjusting the estimate of the surface roughness. For the porous asphalt the coefficient of permeability for the base layer was varied to produce the observed peak base discharge rate.

Simulation results were evaluated on the basis of reproducing observed runoff volumes, peak discharges and response time.

In respect of the Porous Asphalt pavement the calibration of PORPAV was undertaken using records of the sprinkler inflows and discharge measurements from a stormwater event. The simulation results are compared to observed values in Table 9. The cumulative runoff volume and the peak discharge rate were reproduced quite well as demonstrated in Figure 17. The simulated temporal response indicated by the time to peak and detention time, was more rapid than the recorded values, attributable in part to the travel time associated with the exterior drainage channels which were not modelled.

The point is made by Goforth et al that the resolution of the temporal response is dependent on the duration of the simulation time step and that simulation response times within one time step of the observed times represent accurate simulations.

Verififying the calibrated model by simulating an observed event recorded on 1 June 1982, see Figure 18, did not reproduce observed values as well as the calibration set. The discrepancies between the two discharge hydrographs was considered to represent the difference in hydrologic response between the two data sets.

The lattice block pavement was modelled using data generated by sprinklers which represented the storm events. The results are compared to observed values in Table 10.

The discharge hydrograph for the calibration data is presented in Figure 19. The runoff volume and the recession limb of the hydrograph are well reproduced, while the peak runoff rate was overestimated. The simulated temporal response lagged slightly the observed response, although the hydrograph decay was tracked well. The observed discharge characteristics of the second runoff event were well simulated, see Figure 20. The simulated hydraulic response for the third event was quite different from the observed results, see Figure 21. The bimodal peak of the simulated discharge hydrograph reflects the influence of the second burst of recorded inflow, whereas the observed hydrograph does not.

This discrepancy is considered to be possibly due to the second peak not being measured which in turn would explain the discrepancy between observed and simulated volumes.

Diniz and Espey (9) applied PORPAV to simulate the performance of a porous pavement parking area development in The Woodlands, a planned community, near Houston, Texas. Due to the lack of prototypical data from the site, simulations were run using the 100 year rainfall for the Houston area. With pavement and base permeabilities of 40in/hr and 80in/hr no surface runoff was generated. Surface runoff was only generated by reducing the permeabilities to 15in/hr and 30in/hr respectively.

Niemczynowicz (31) using a Storm Water Management Model simulated the effect of constructing all the pavements in the City of Lund, Sweden with permeable pavement of the Unit Superstructure. The model had previously been calibrated with data from measured rainfall and runoff events. The simulated effect of replacing existing pavement with Unit Superstructure was to attenuate the peak flows in the combined sewer and storm water conduits by 75% and the peak flow in the storm water system by 90%.

A similar simulation applied to a 0.2 sq.km. catchment in Gothenburg showed a peak flow reduction of 80%, Niemczynowicz and Hogland (32).

Tamai et al (44) verified their mathematical model, developed to treat a two-dimensional simulation of unsaturated seepage, against experimental data undertaken by Vauclin et al (49). Figure 22 illustrates the calibration of the model against the experimental using an hydraulic conductivity of 35cm/hr.

The model was then calibrated against data obtained from the pervious pavement associated with a baseball field constructed at the University of Tokyo. Figure 23 shows a section through the pavement. The outflow hydrograph simulated by the model is shown in Figure 24, with hydraulic conductivities of 0.22, 0.07 and 0.01cm/s respectively for the asphalt, crusher run and sand; air-entry potential values of -4cm and -15cm for the crusher run and sand layer; saturated moisture contents of 0.5 and 0.4 for the crusher run and sand layer and values of constant b, see Equation 4 of 3.0, 5.0 and 1.0 respectively for the asphalt, crusher run and sand layer.

It was found necessary to increase the value of b above that suggested by Campbell (2) in order to obtain a more sensitive response between the rainfall and groundwater runoff.

Tamai et al (44) then proceeded to apply the model to a further rainfall event recorded at the baseball field again with the pavement underlain by an impervious sheet, see Figure 25. Reasonable agreement between observed and calculated runoff hydrographs was only obtained by reducing the maximum flow capacity of the drainage pipe associated with the pavement and attributing an initial overestimate of the predicted runoff to not taking account of clogging of the drain pipe.

The remaining discrepancy between observed and calculated runoffs could only be rectified by adjusting the hydro-geological parameters of the pavement and it was considered that in order to simulate the permeability of an unsaturated pavement that modifications would be necessary to the functional form in the model representing the unsaturated conditions.

Applying the model to a pervious pavement laid directly onto a natural subsoil base produced an unsatisfactory agreement, see Figure 26. Calculated peak outflows are similar in magnitude to the observed peaks but are temporally advanced by the order of three hours. The recessional arms of the peaks are not well replicated. Tamai et al considered that the simplified treatment applied in the model was not adequate and that a larger scale simulation should be adopted where the computational zone was extended to the phreatic surface.

Ichikawa and Harada (22) similarly working on data from the same baseball field simulated the runoff associated with two recorded rainfall events.

Figure 27 shows the comparison between the simulated and observed cumulative volume of drained water for the two events. The effects of neglecting hysteresis are shown by the fact that the simulated values are larger than the observed values at the time when the rainfall has temporarily stopped. The difference is not significant in terms of volume.

Using equations developed from experimental work, Wada and Muira (51) simulated the effect of replacing 76% of the roads, 38% of the roofing and 9% of the open space in an urban study area in Kobe City, Japan with permeable pavement or pervious material. This increased the permeable nature of the catchment from 0% to 25% and its effect was to reduce the storm water runoff by 33%.

Based on prototype measurements, van de Ven and Zuidema (48) chose the Hillel and Gardner infiltration model to simulate the infiltration through brick and tiled surfaces laid on sand beds. Calculated infiltration depths ranging from 11 to 99mm were predicted for time periods of between 1 to 12 hours.

Jacobsen and Harremoes (25) used an infiltration formula based on formulae proposed by Green and Ampt (14) and later by Mein and Larson (27). The model was used to simulate a time series of rain and evaporation data measured from a granite set and asphaltic pavement constructed in Lyngby, Denmark. The runoff volumes generated were in agreement with the recorded volumes, see Table 11b. Based upon the measured and predicted runoff volumes, runoff coefficients of 0.90, 0.80, 0.10, and 0.01 were estimated for roofs, streets, semi-pervious and pervious areas, see Table 11c.

Simulations were then run for a city and a residential area using four alternative surface distributions. The initial surface distributions for both areas are shown in Table 11a. Additional surface distributions were:

Alternative 2 : all streets (impervious surfaces minus roofs) assumed to be semi-pervious surfaces, all other surfaces as for Tables 11d,e.

Alternative 3 : all roofs are assumed to be drained to an infiltration system, all other surfaces as for Table 11d,e.

Alternative 4 : all streets are assumed to be semi-pervious surfaces and all roofs are assumed to drain to an infiltration system, all other surfaces as Table 11d,e.

For both the city and the residential area the change of the pavement from impervious to semi-pervious or, a change of the drainage system for the storm water collected from the roofs into an infiltration system, leads to a reduction in runoff volume of about 30-60%. The effect of a combined change is more pronounced leading to a runoff reduction of 90%, see Table 11d,e.

11. ADVANTAGES AND DISADVANTAGES OF PERMEABLE PAVEMENT

Advantages

Day et al (6), Field et al (10), Hogland and Spangberg (20), Pratt et al (35), Scherocman (40), and Thelen et al (46) all consider the most important benefits from permeable pavements to be:

- attenuation of the runoff rate and volume.
- enhancement of water quality in areas where the runoff generated from impervious areas has the potential for becoming contaminated.

with additionally :

- improved erosion control.
- reduction or abatement in the need for curbs and storm sewer installation or expansion.
- retention of natural vegetation and drainage patterns.
- reduction or elimination of the nuisance factor to pedestrian and motorist from standing puddles and temporary storage in carparks and streets.
- increase in the amount of groundwater recharge to local aquifers in water defficient areas.
- improved road safety due to higher friction coefficient, because of reduced hydroplaning and improved visibility.

Smith (42), and Thelen, (46) also identified the following benefits :

- aesthetic reasons.
- temperature control by use of coloured surfaces.
- directional control of traffic by use of coloured surfaces.

Disadvantages

Porous pavements are considered to have few disbenefits. Field et al (10), Hogland et al (19) considered the main concern to be :

- susceptibility to clogging

Other concerns related to:

- spillage of petrol from vehicles parked on porous pavement car parks constructed from porous asphalt will break down the asphalt binder.

- asphaltic porous pavements could lead to more subsurface pollution due to the inability of the porous pavement and underlying soils to filter and purify contaminants in runoff.

Additionally Scherocman (40) considered disadvantages to include

- necessity for sandy subgrade soil with high permeability.
- passage of water through pavement to soil weakens the subgrade.
- porous or open graded asphalt is not as strong as a dense graded mixture.

- the requirement for thicker pavements on downhill slopes to prevent filling and overflow of the pavement.
- accelerated wear and failure of pavement due to presence of water in mixing plant preventing asphalt cement binder coating the aggregate.

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TABLES

TABLE 1 : Porous pavement peak runoff rate for Gates-Chile-Ogden Sewage Treatment Plant, Rochester, New York (Murphy et al, 1981)

Date	Rainfall (in/hr)		Pavement runoff (cusecs)	
	Total (in)	Peak (in/hr)	Impervious	Porous
02/09/79	0.69	3.00	0.4100	0.0440
06/09/79	0.48	0.11	0.0200	0.0100
13/05/80	0.37	0.30	0.0089	0.0048
17/05/80	0.59	0.24	0.1400	0.0900
31/05/80	0.41	1.60	0.4970	0.4000
01/06/80	0.49	1.08	0.8800	0.4000
15/06/80	0.15	1.20	0.0046	0.0006
19/06/80	0.99	4.50	0.2030	0.0280
26/06/80	0.30	1.20	0.2260	0.0610
28/06/80	0.53	0.60	0.1020	0
02/07/80	0.20	0.60	0.0880	0.0320
15/07/80	0.11	0.40	0.0700	0
17/07/80	0.40	1.54	0.4970	0.3800
20/07/80	0.07	1.20	0.0030	0
22/07/80	1.00	1.39	0.4970	0.4970
27/07/80	0.25	1.28	0.2260	0.0250
29/07/80	0.09	0.96	0.0410	0
02/08/80	0.21	2.60	0.2800	0.2300
05/08/80	0.60	2.20	0.2420	0.1200
15/08/80	0.89	1.48	0.4970	0.9500

TABLE 2 : Controlling effect of Stormwater Infiltration Facility on Surface Runoff, Tokyo (Minigawa, 1990)

	Name of housing complex		
	Akishima	Tsujido	Kohoku NT
Rainfall amount (mm)	69.30	35.32	75.18
Average rainfall intensity (mm/hr)	4.47	3.80	3.00
Impervious area			
Runoff (mm)	37.59	23.03	67.66
Runoff Coefficient	0.52	0.66	0.90
Infiltration area			
Runoff (mm)	5.48	1.22	0.00
Runoff Coefficient	0.054	0.031	0.000
Time lag (hrs)	8.9	3.5	-

TABLE 3 : Runoff coefficients for Grasscrete Porous Pavements. (Day, 1978)

Percentage of open bottom area	Rainfall (min)	Moderate soil Surface slope (%)		
		2	4	7
30	30	0.02	0	0.02
	60	0.13	0.15	0.18
	90	0.23	0.25	0.28
	120	0.29	0.31	0.35

Hydraulic conductivity (in/hr)	1.66
Rainfall intensity (in/hr)	4.15

TABLE 4 : Stormwater runoff comparisons of a grid and an asphalt lot. (Smith, 1984)

Date	Rainfall		Runoff volume from grid lot	Runoff coefficient		Peak Flow	
	Total	Volume on grid lot		Grid	Asphalt (1)	Grid	Asphalt (1)
	cm	cu.m.	cu.m.			litres/sec.	
01/07/81	4.06	111.13	10.78	0.10	1.00	9.2	60.8
13/07/81	3.30	92.04	18.34	0.20	1.00	21.8	223.6
21/07/81	0.41	11.42	0	0	1.00	0	3.1
27/07/81	0.81	22.73	0.69	0.03	1.00	0.1	7.5
28/07/81	0.13	3.77	0	0	1.00	0	3.8
03/08/81	0.10	2.97	0	0	1.00	0	1.5
05/08/81	1.70	47.70	5.84	0.13	1.00	2.8	19.5
07/08/81	0.41	11.42	0.76	0.08	1.00	1.1	14.1
01/09/81	1.93	53.09	13.50	0.25	1.00	12.7	21.5
02/09/81	0.69	19.11	0	0	1.00	0	28.9
03/09/81	1.68	46.72	16.31	0.35	1.00	20.9	24.4

(1) Values based on computational simulation of asphalt lot using rainfall total and rainfall volume from grid lot.

TABLE 5 : Comparison of constituent concentrations for Porous and Conventional pavements (Goforth et al, 1983)

Constituent	Pavement type	Average Concentration (mg/l) Event			Flow weighted average (mg/l)
		1	2	3	
Total suspended solids	Porous asphalt	389	134	44.1	175
	Lattice block	29.1	17.4	30.4	24.5
	Conventional asphalt	39.7	51.7	-	43.0
Chemical oxygen demand	Porous asphalt	31.3	15.6	29.2	24.2
	Lattice block	25.1	33.5	44.4	33.4
	Conventional asphalt	19.9	57.0	-	30.0
Total Nitrogen	Porous asphalt	1.82	2.22	4.71	2.96
	Lattice block	1.48	2.30	2.09	1.79
	Conventional asphalt	-	2.88	-	2.88
Total Kjeldhal Nitrogen	Porous asphalt	0.93	1.46	3.53	2.24
	Lattice block	1.25	1.70	1.79	1.57
	Conventional asphalt	0.87	2.33	-	1.27
Lead	Porous asphalt	0.024	0.007	0.013	0.014
	Lattice block	0.009	0.015	0.011	0.012
	Conventional asphalt	0.009	0.020	-	0.012
Zinc	Porous asphalt	0.020	0.018	0.054	0.031
	Lattice block	0.026	0.022	0.008	0.020
	Conventional asphalt	0.007	0.026	-	0.012

TABLE 6 : Comparison of constituent concentrations for Porous and Conventional pavements (Balades and Chantre, 1990)

Constituent	Pavement type	Concentration gm/yr/1000 cu.m.
Chemical oxygen demand	Porous asphalt	14695
	Conventional asphalt	123903
Suspended matter	Porous asphalt	61616
	Conventional asphalt	121353
Lead	Porous asphalt	5.6
	Conventional asphalt	76.3

TABLE 7 : Pollutant concentration in the drainage water during the snowmelt test. (Hogland et al, 1990)

Physical and chemical properties of snow and drain-water

	Snow	Drain-water
pH	7.5	7.5
Conductivity (us/cm)	55	361
Pollutant (mg/l)		
Suspended solids	805	38
Total solids	816	216
Fixed solids	773	219
Chloride	14	17
Total Phosphorus	0.14	0.04
Kjeldhal Nitrogen	0.43	0.50
NH_4-N	0.23	0.35
NO_3-N	0.14	2.39
NO_2-N	0	0.02
Cu	0.38	0.22
Cr	0.47	0.02
Al	18.00	2.39
Zn	0.58	0.22
Pb	0.04	0.02
Cd	0.03	0.04

TABLE 8 : Pollutant concentrations in runoff from Grasscrete and Concrete slab. (Day et al, 1981)

Pollutant (mg/l)	Grasscrete	Concrete slab
	(filtered samples)	
Total PO_4-P	0.47	0.51
Ortho PO_4-P	0.24	0.18
Organic PO_4-P	0.19	0.23
$NO_3 + NO_2$-N	1.84	0.72
NH_3-N	1.61	1.03
Organic N	3.83	2.10
Total Organic Carbon	19.49	7.22
Pb	0.061	0.184
Zn	0.194	0.252
Cr	0.054	0.071

TABLE 9 : Runoff simulation for porous asphalt lot. (Goforth et al, 1983)

	Peak flow (cfs)	Time to peak (min)	Runoff volume (cu.ft.)	Detention time (min)
Calibration				
Storm 22/3/82				
Observed	0.269	58	815	42
Simulated	0.273	50	815	28
Deviation	+0.004	-8	0	-14
Verification				
Storm 1/6/82				
Observed	0.237	53	721	42
Simulated	0.514	55	1409	25
Deviation	+0.283	+2	+688	-17

TABLE 10 : Runoff simulation for lattice block lot. (Goforth et al, 1983)

	Peak flow (cfs)	Time to peak (min)	Runoff volume (cu.ft.)	Detention time (min)
Calibration				
Storm 2/3/82				
Observed	0.034	55	101	11
Simulated	0.052	75	96	18
Deviation	+0.018	+20	-5	+7
Verification				
Storm 11/3/82				
Observed	0.078	40	201	12
Simulated	0.063	30	184	6
Deviation	-0.015	-10	-17	-6
Verification				
Storm 18/3/82				
Observed	0.113	24	129	11
Simulated	0.185	35	281	4
Deviation	+0.072	+11	+152	-7

TABLE 11 : Runoff volumes, runoff coefficients and surface types. (Jacobsen and Harremoes, 1981)

a) Surface distribution

Type of area	Impervious (%)		Semi-pervious	Pervious
	Roof	Street	(%)	(%)
City	15	40	20	25
Residential	15	10	5	70

b) Runoff volume recorded from semi-pervious catchment compared with computed volumes for semi-pervious and impervious catchment.

Period of data collection	Total rainfall depth recorded	Total runoff recorded	Total runoff computed	
			Paving stones	Asphalt
	(mm)	(mm)	(mm)	
27/7/78 to 18/12/78	256	28	24	208

c) Runoff coefficients for impervious, semi-pervious and pervious surfaces.

Type of surface	Impervious		Semi-pervious	Pervious
	Roof	Street		
Runoff coefficient	0.90	0.80	0.10	0.01

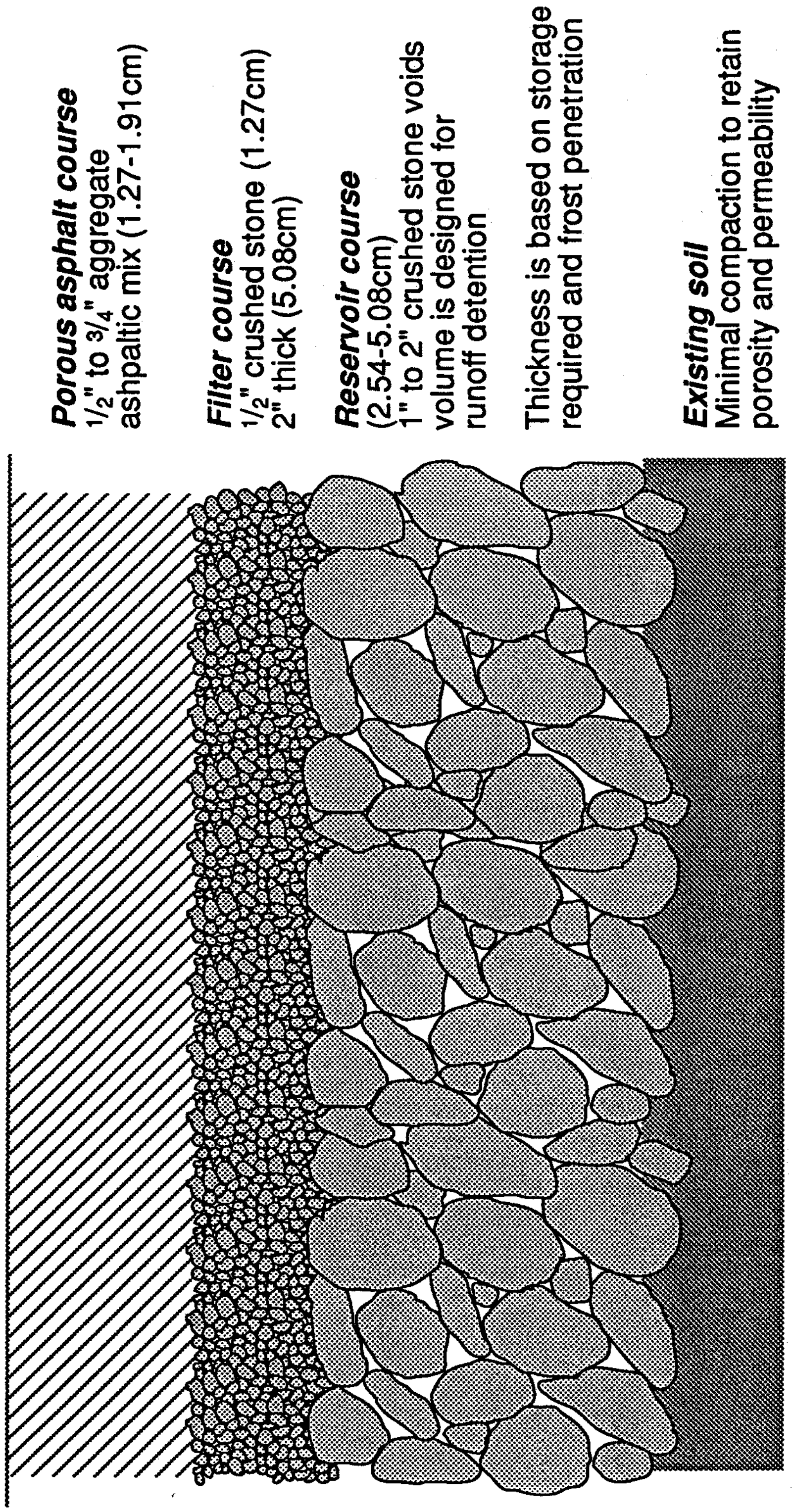
d) Total runoff volume per unit area for a city area

Alternative No.	Impervious		Semi-pervious	Pervious	Total
	Roof	Street			
1	13.5	32.0	2.0	0.3	48
2	13.5	4.0	2.0	0.3	20
3	0.0	32.0	2.0	0.3	34
4	0.0	4.0	2.0	0.3	6

e) Total runoff volume per unit area from a residential district

Alternative No.	Impervious		Semi-pervious	Pervious	Total
	Roof	Street			
1	13.5	8.0	0.5	0.7	23
2	13.5	1.0	0.5	0.7	16
3	0.0	8.0	0.5	0.7	9
4	0.0	1.0	0.5	0.7	2

FIGURES



PGH/1/4-91/LO

Fig 1 Porous ashphalt pavement section (Diniz, 1980)

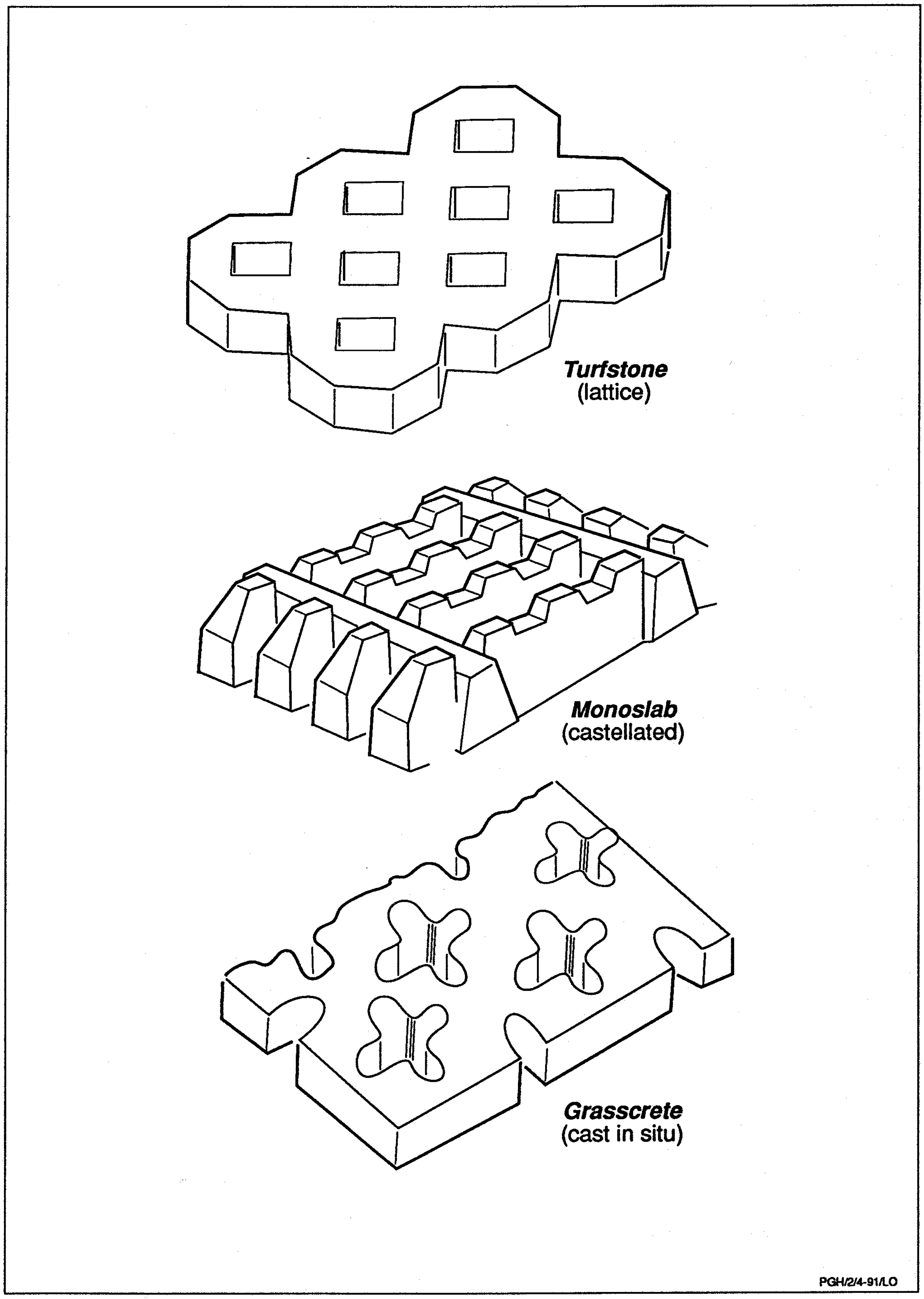


Fig 2 Concrete grid paving blocks (Day et al, 1981)

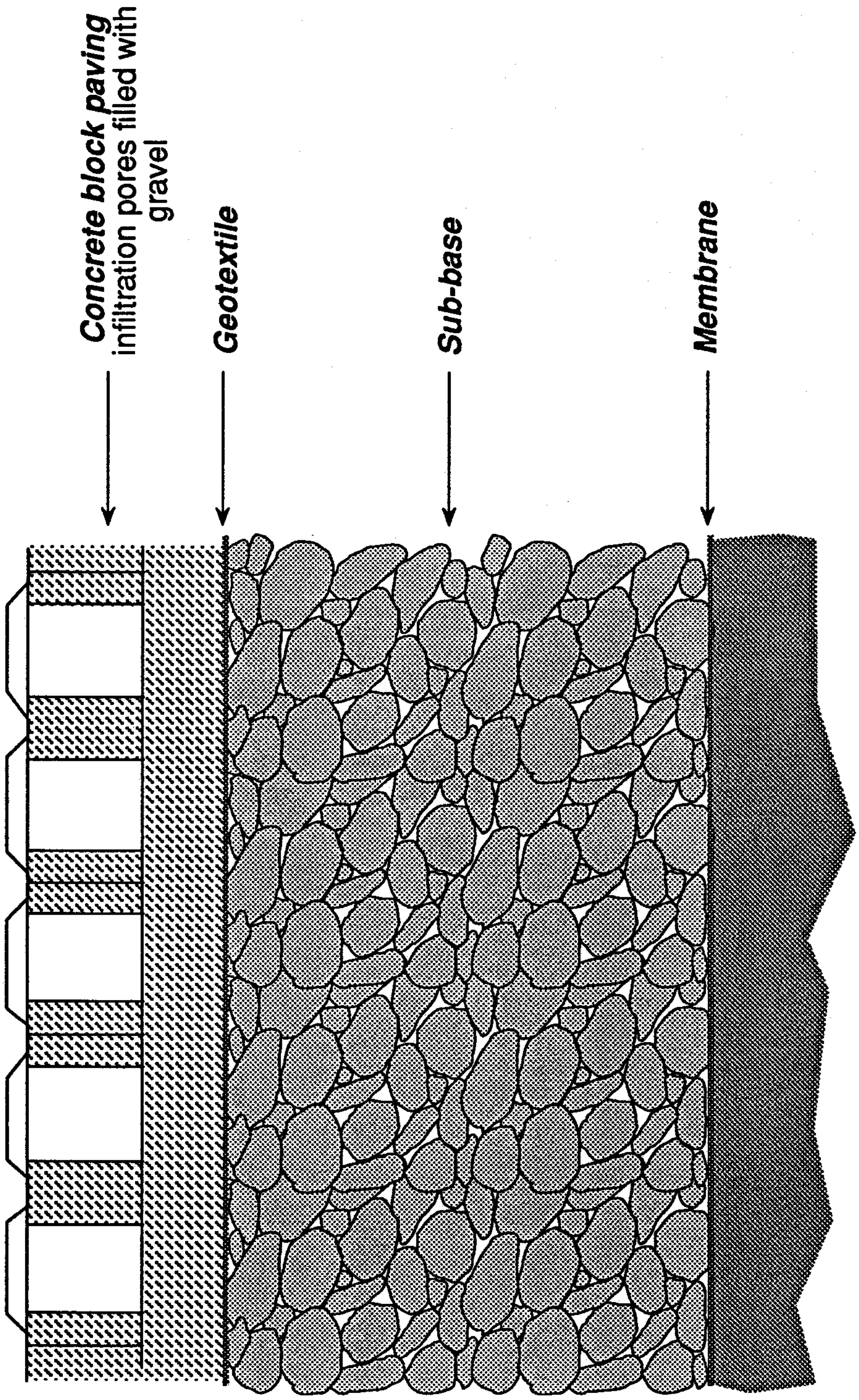
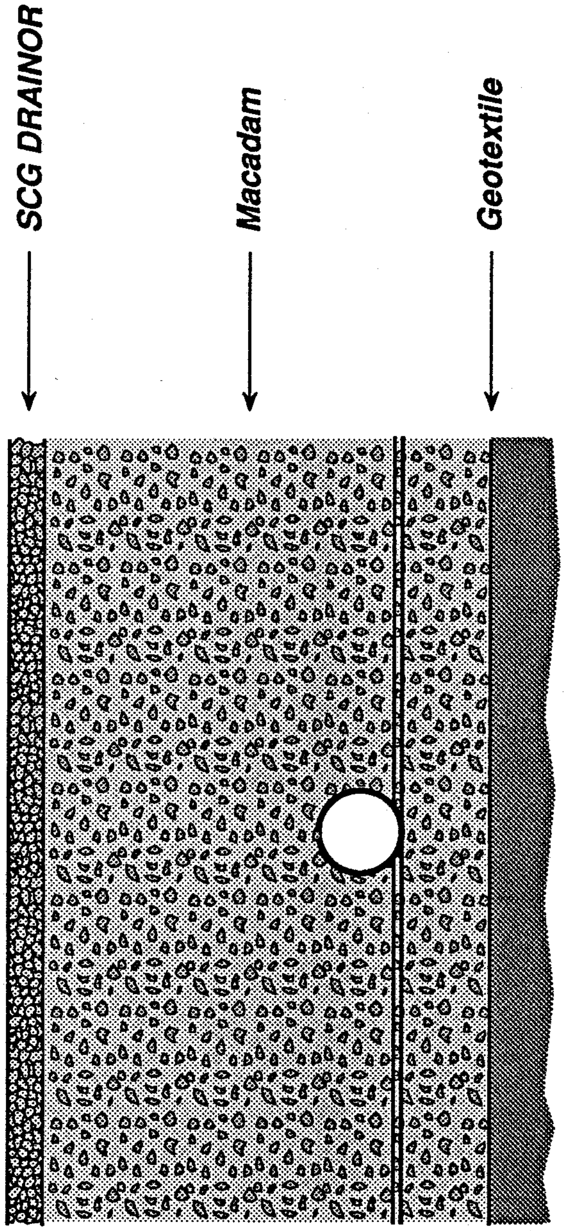


Fig 3 Porous block pavement section (Pratt and Mantle, 1989)



PGH/4/4-91/LO

Fig 4 The Unit Superstructure (Hogland et al, 1987)

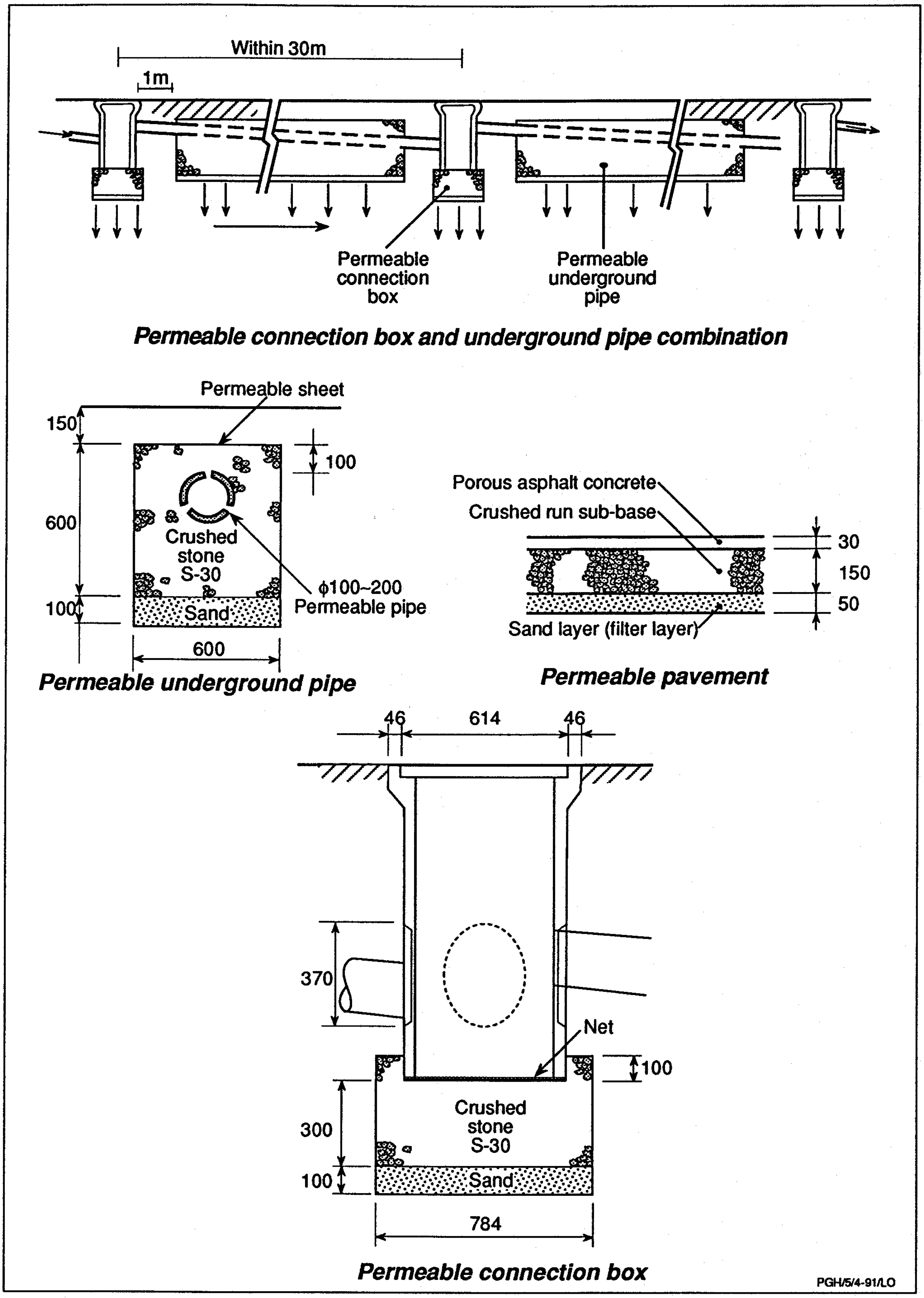


Fig 5 Stormwater infiltration systems (Minigawa, 1990)

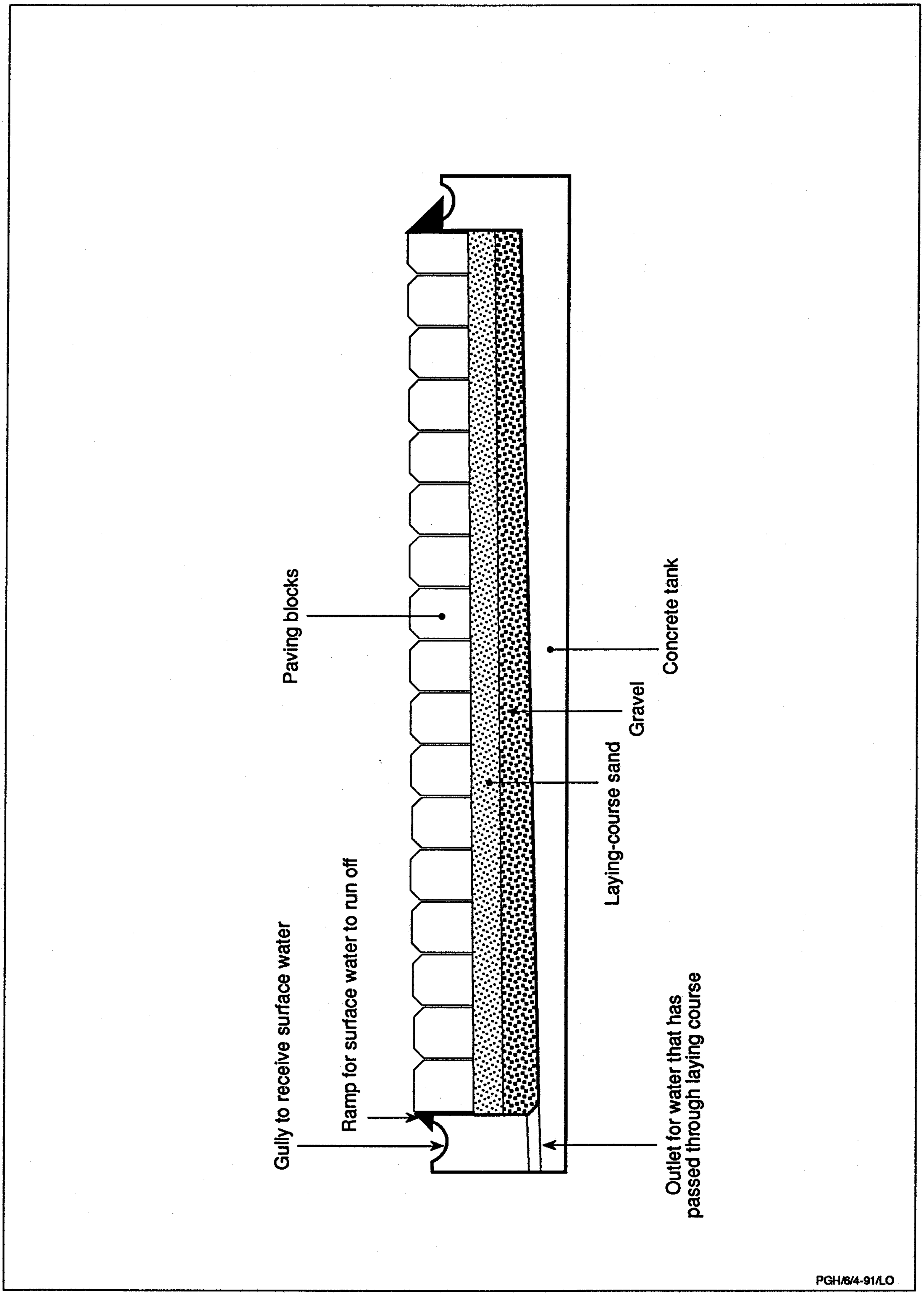
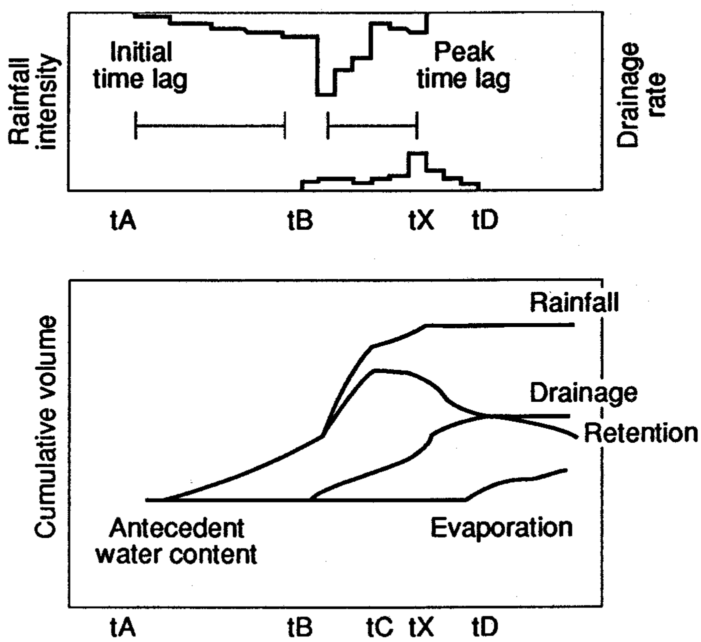


Fig 6 Concrete block paving section (Clark, 1979)



Water balance: $R(t) = AWC + I(t) - D(t) - E(t)$

where:

R(t)	:	the cumulative volume of retention
AWC	:	the antecedent water content, which is equal to R(tA)
I(t)	:	the cumulative volume of rainfall
D(t)	:	the cumulative volume of drainage
E(t)	:	the cumulative volume of evaporation

time parameter:

tA	:	time rainfall is started
tB	:	time drainage is started
tC	:	time at which a maximum volume of retention is recorded
tX	:	time rainfall if finished
tD	:	time drainage is finished

PGH/7/4-91/LO

Fig 7 Drainage infiltration strata dynamics (Itchikawa and Harada, 1990)

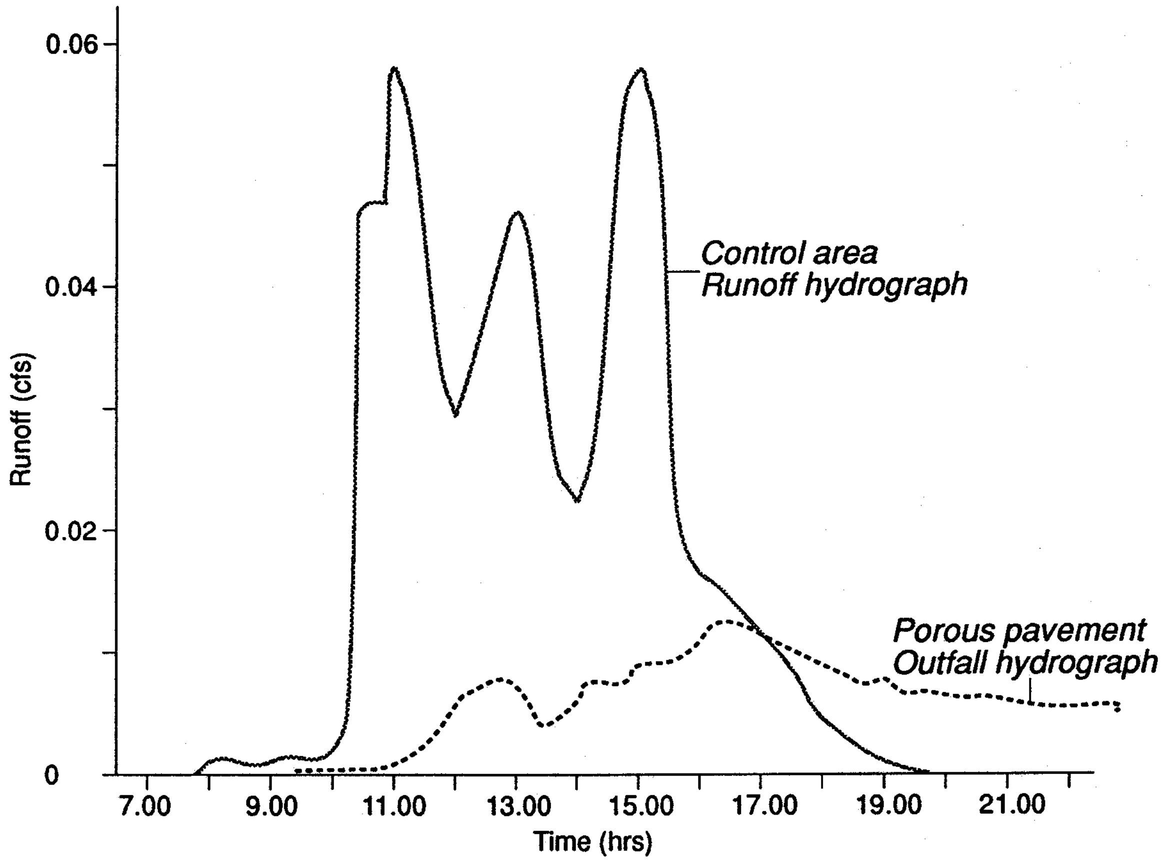


Fig 8 Porous asphalt pavement runoff hydrograph (Murphy et al, 1981)

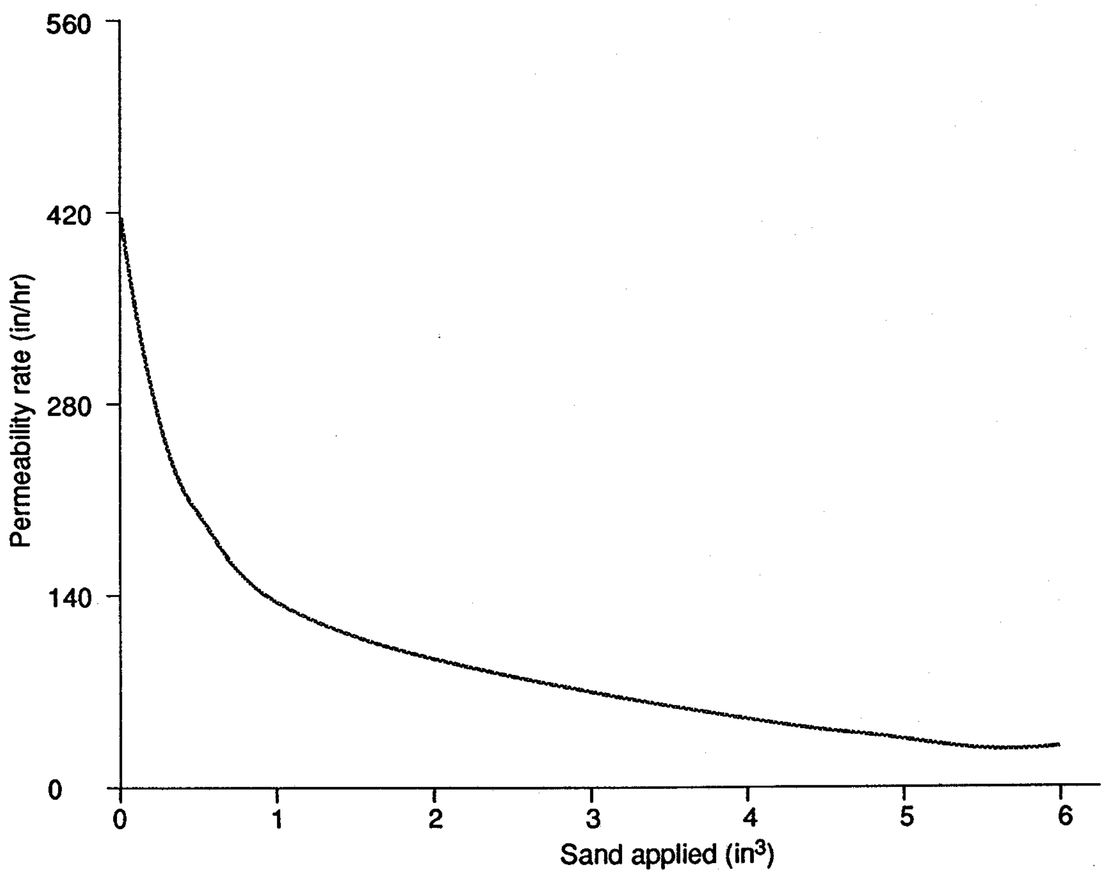
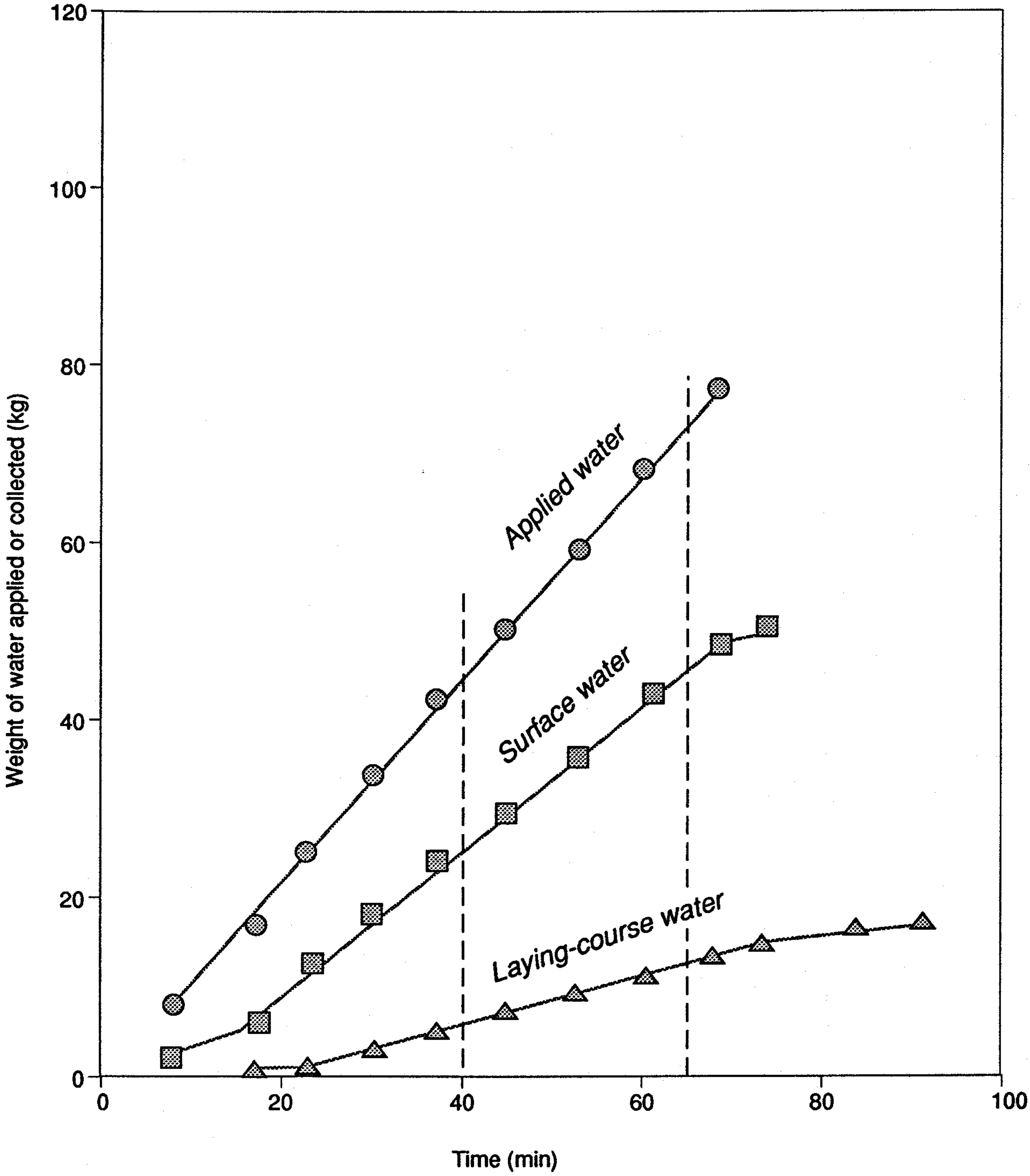


Fig 9 Porous asphalt pavement permeability – influence of clogging by sand (Murphy et al, 1981)



Simulated rainfall level = 22mm/hr

$\frac{\text{Surface water flow}}{\text{Applied water flow}} = 70\%$ $\frac{\text{Laying course water flow}}{\text{Applied water flow}} = 24\%$

PGH/10/4-91/LO

Fig 10 Concrete block paving – infiltration rate with open joints (Clark, 1979)

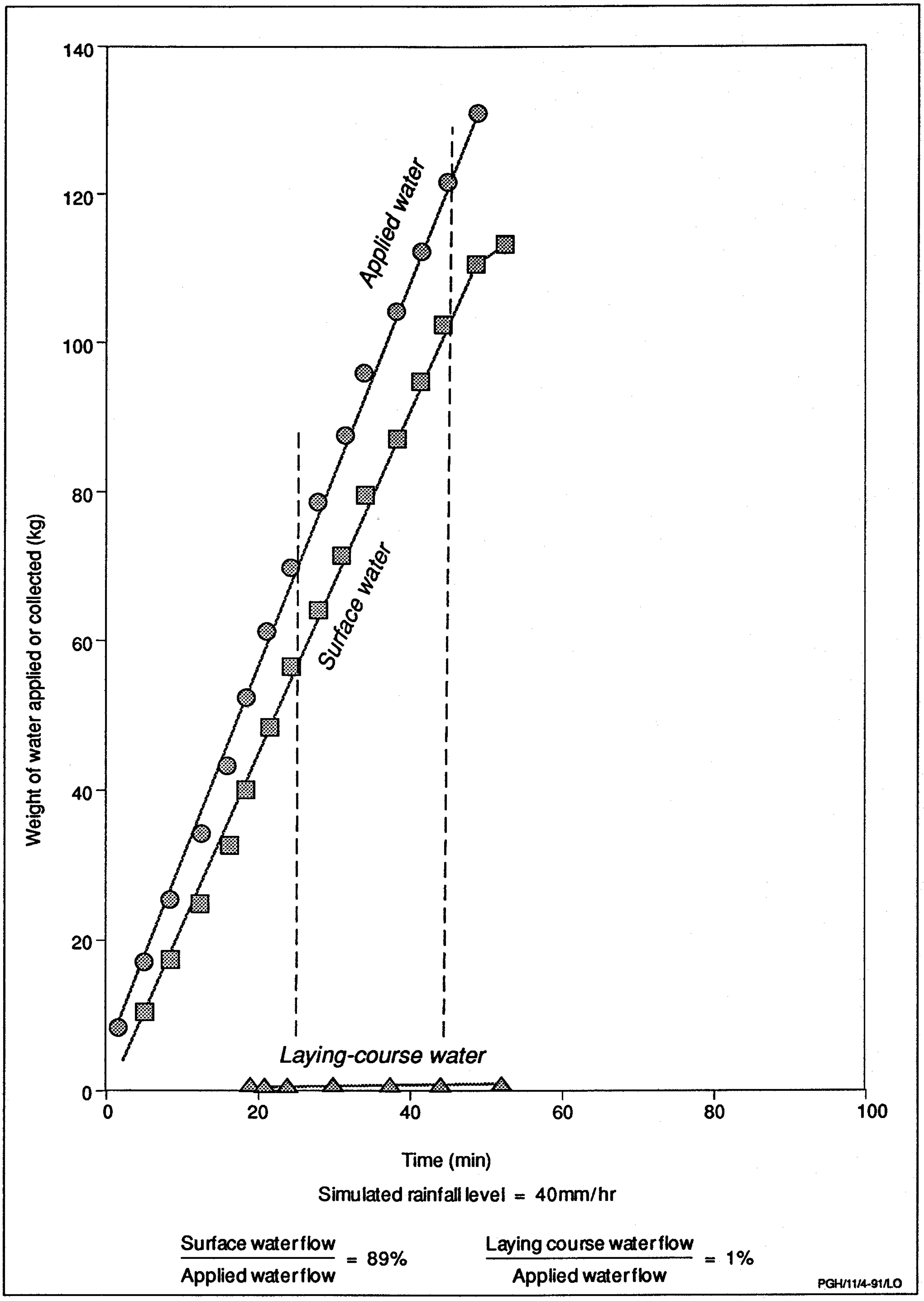


Fig 11 Concrete block paving – infiltration rate with clogged joints (Clark, 1979)

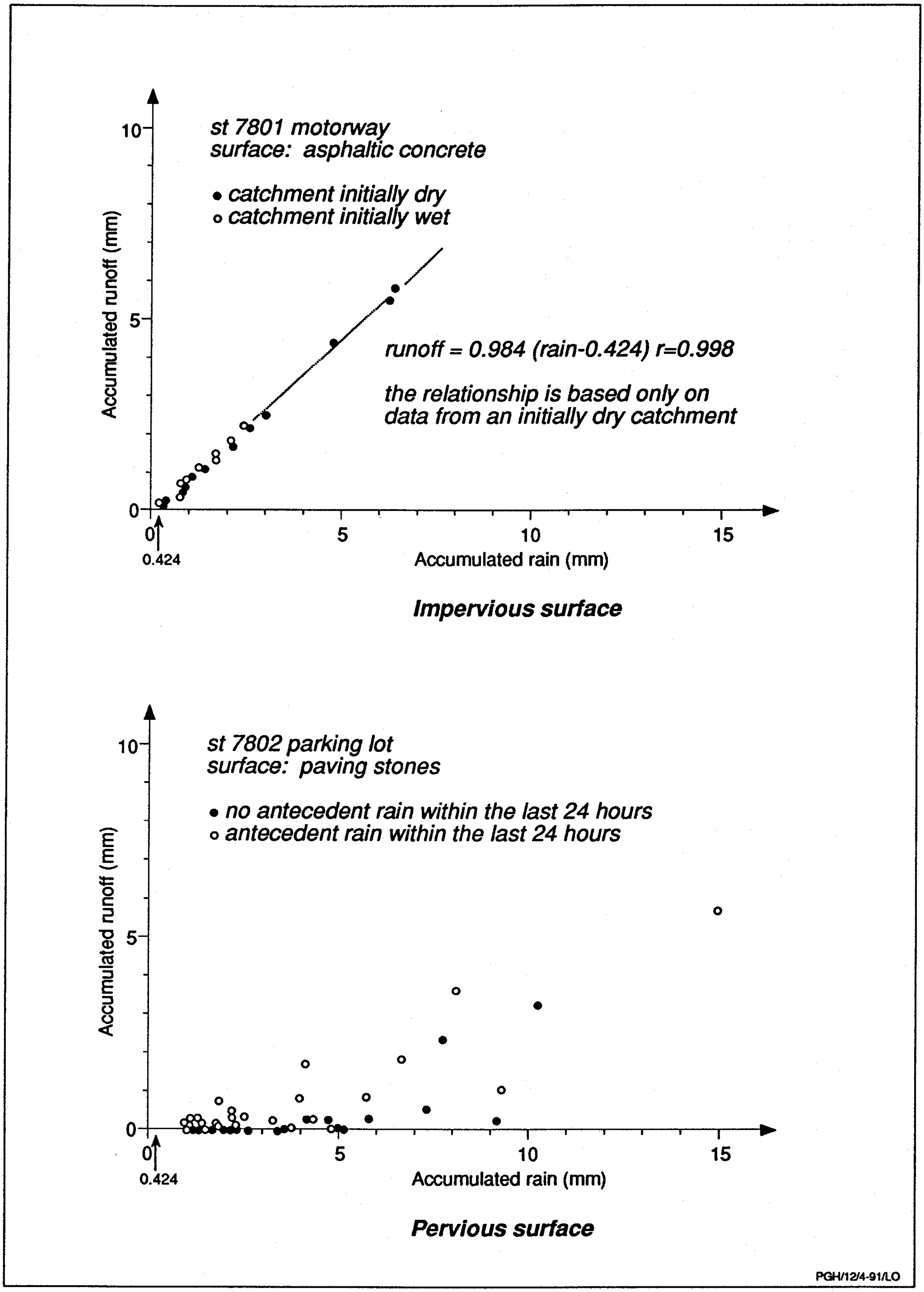
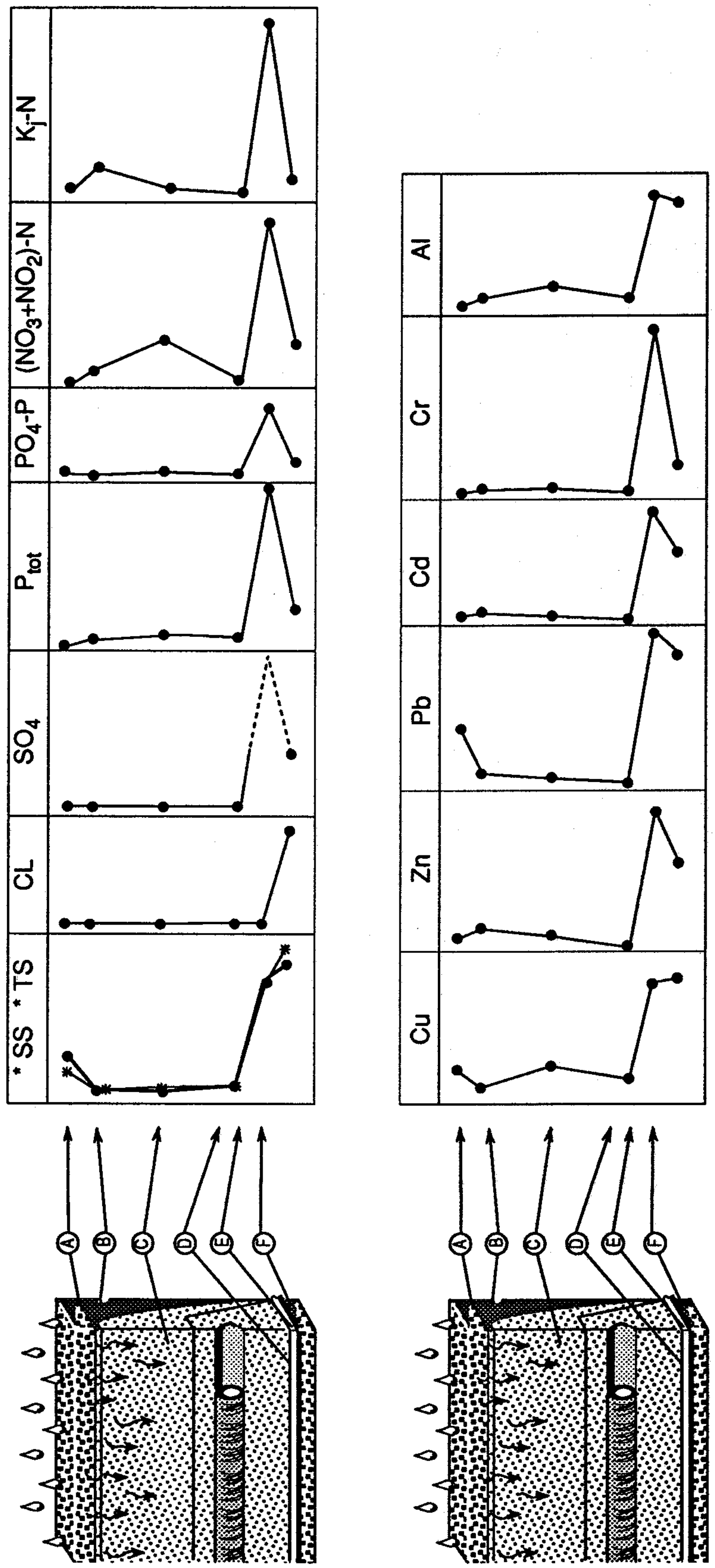


Fig 12 Set paving – measured runoff volume per unit area vs main depth (Jacobsen and Harremoes, 1981)



PGH/13/4-91/LO

Fig 13 Pollutant distribution in the Unit Superstructure (Hogland et al, 1990)

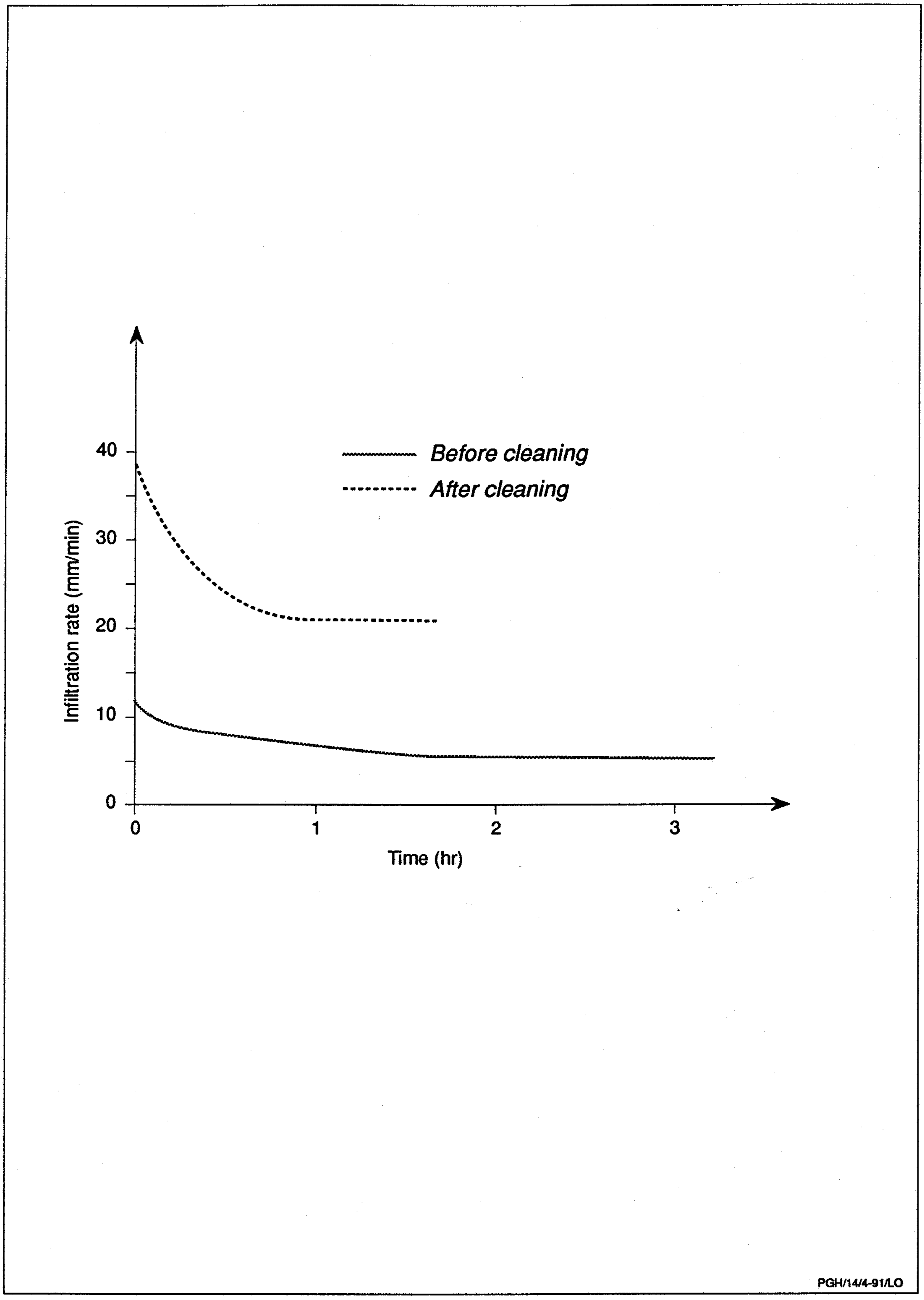
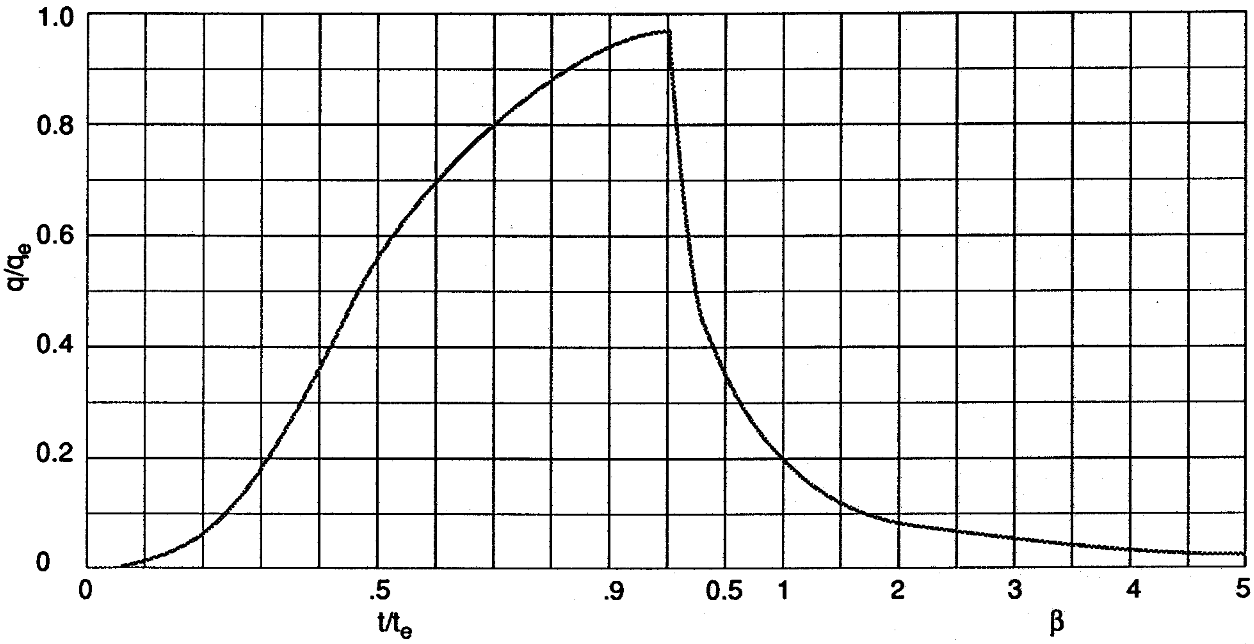


Fig 14 Clogging and cleaning – effect on permeable pavement infiltration rates (Stenmark, 1990)



PGH/15/4-91/LO

Fig 15 Dimensionless hydrograph of overland flow (Izzard, 1946)

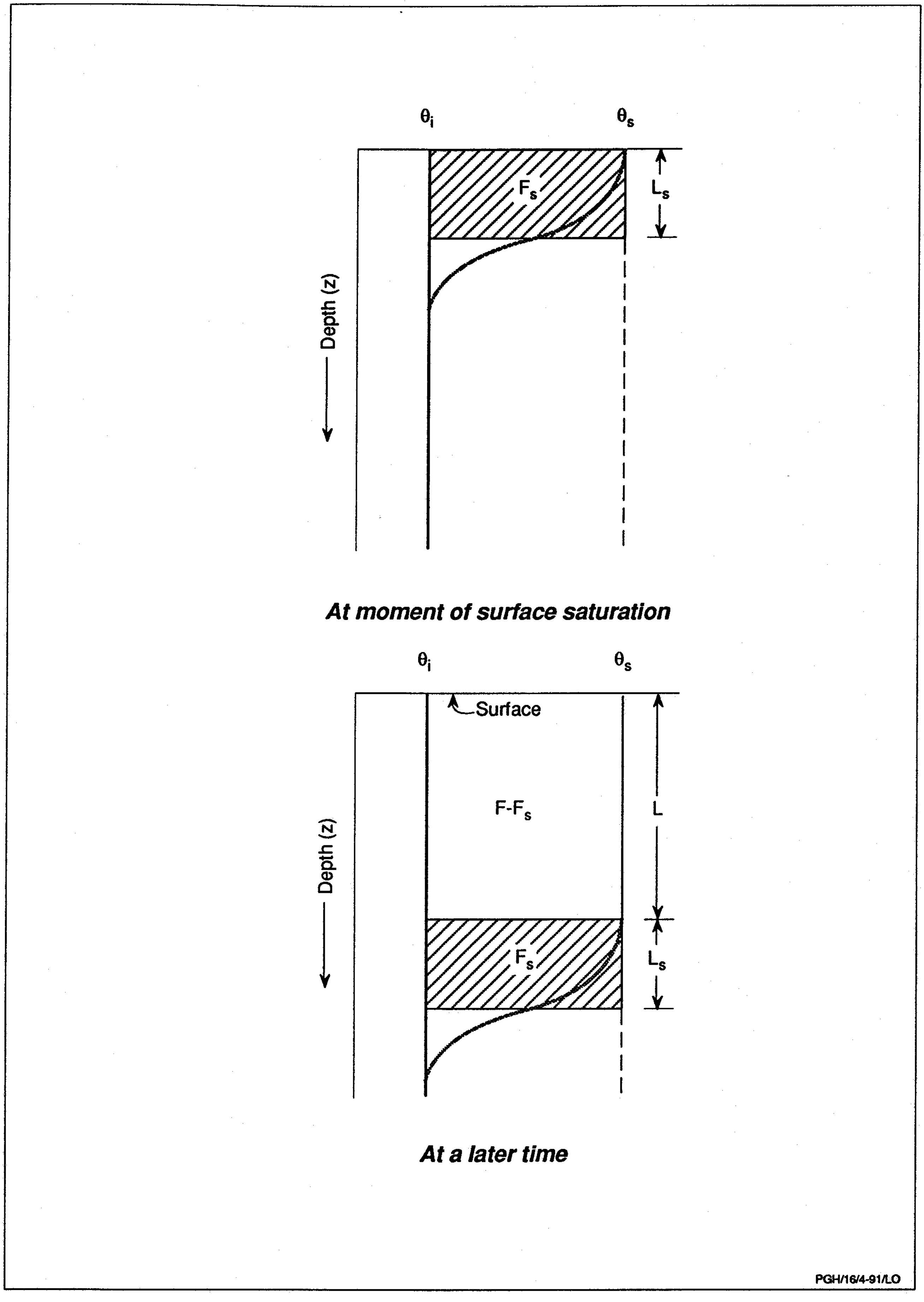


Fig 16 Generalized soil moisture profiles during infiltration (Mein and Larson, 1973)

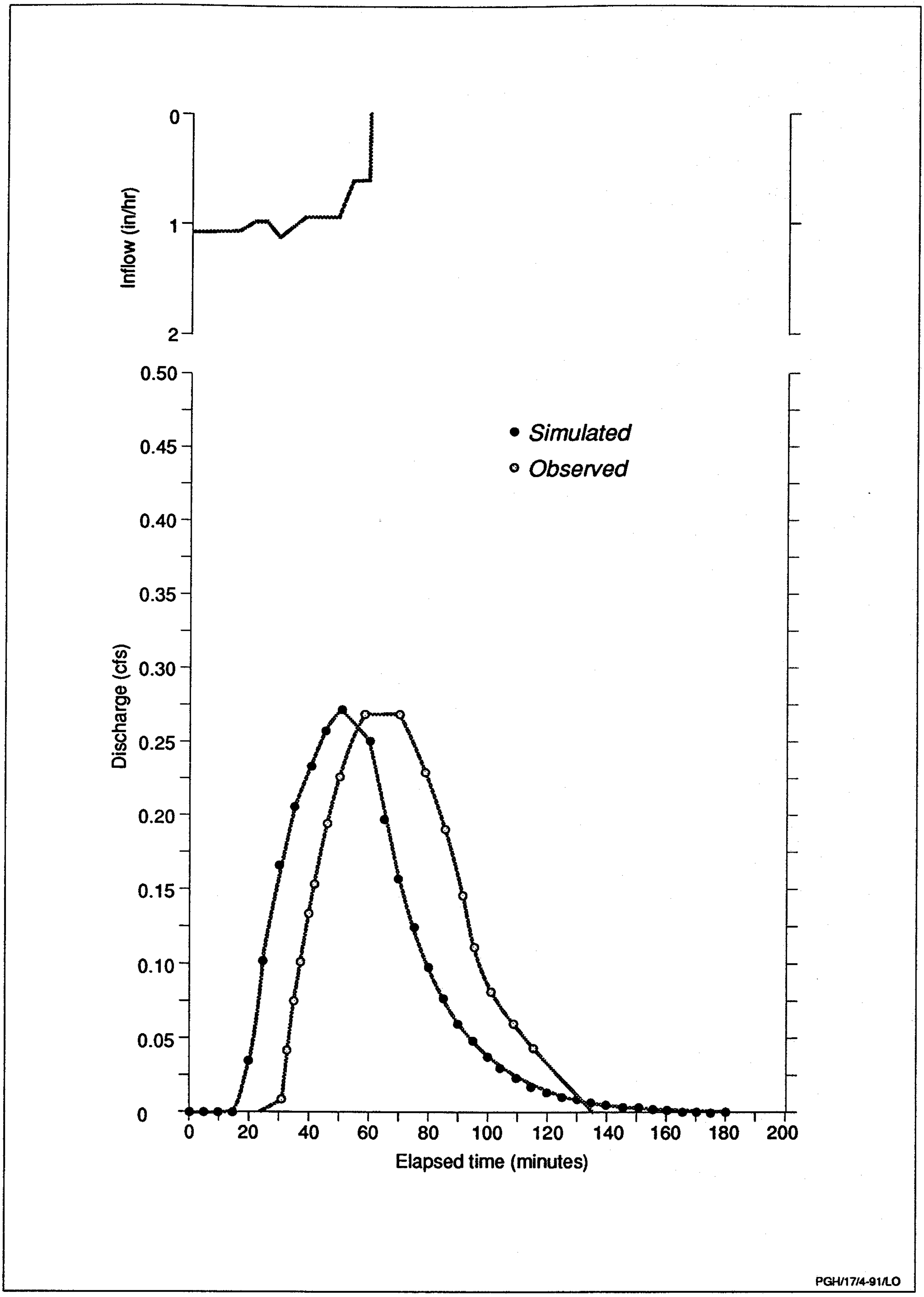


Fig 17 Porous asphalt pavement – simulated/observed runoff hydrographs for storm event of 22/3/1982 (Goforth et al, 1983)

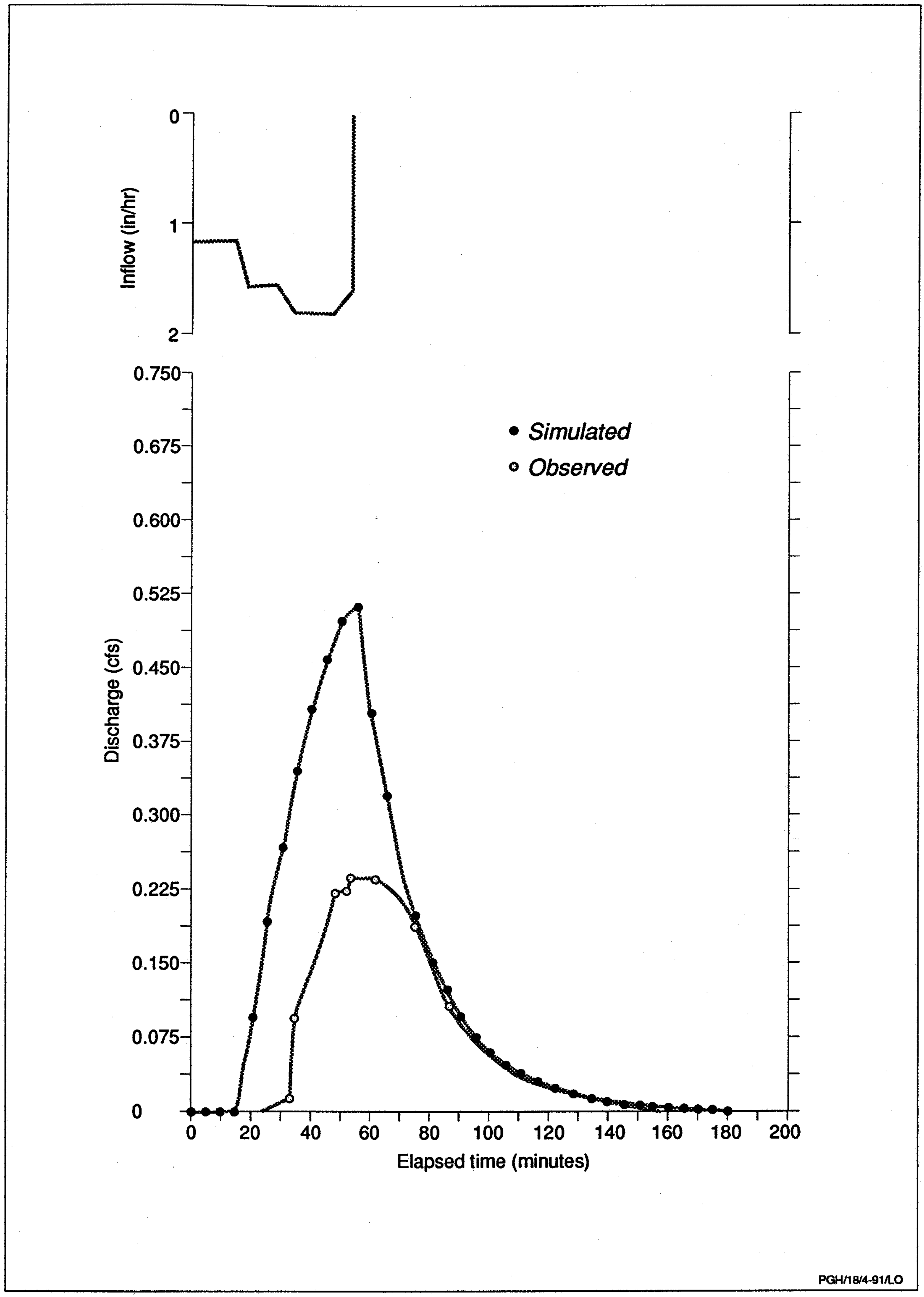
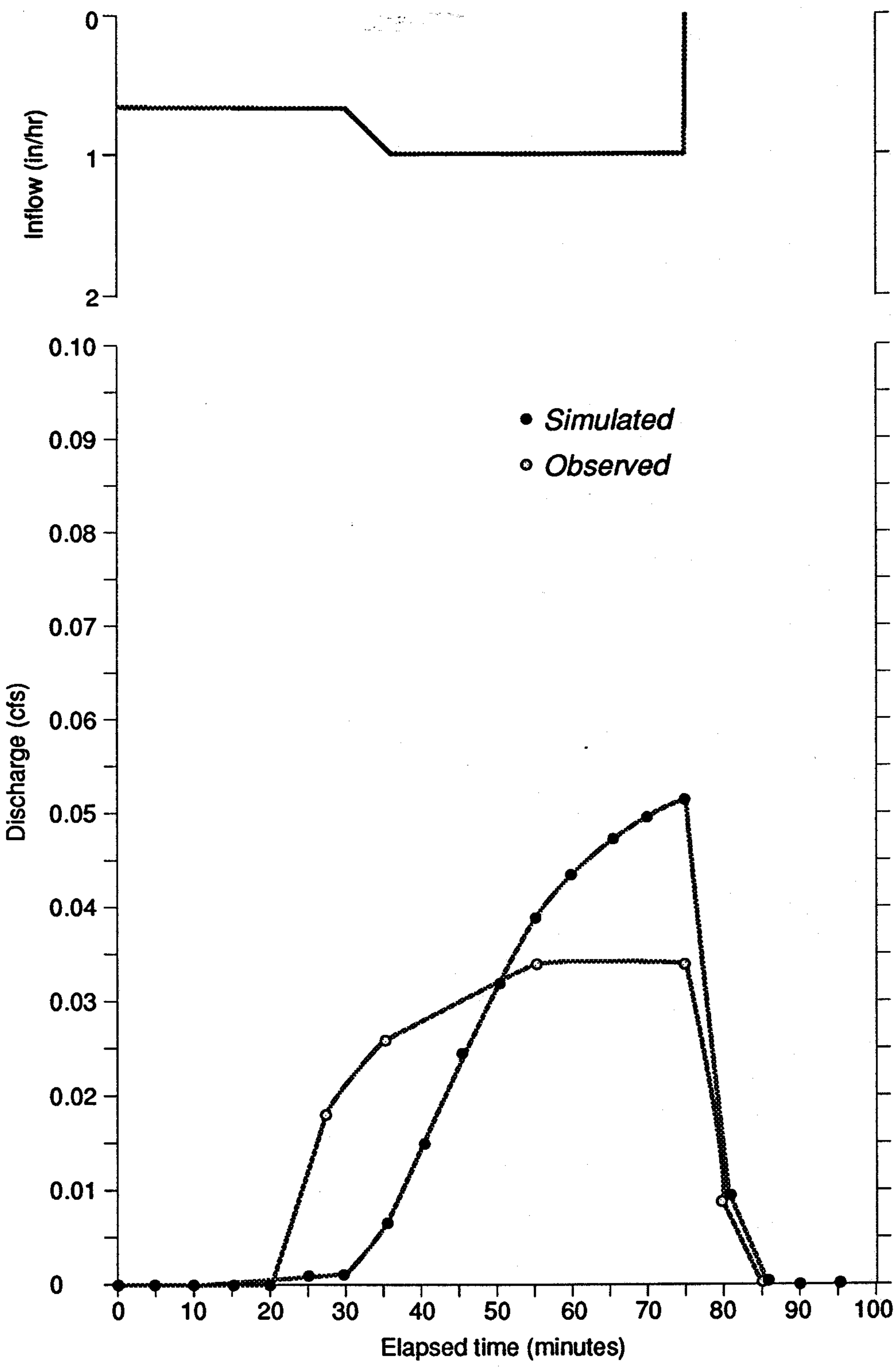


Fig 18 Porous asphalt pavement – simulated/observed runoff hydrographs for storm event of 1/6/1982 (Goforth et al, 1983)



PGH/19/4-91/LO

Fig 19 Lattice block pavement – simulated/observed runoff hydrographs for storm event of 2/3/1982 (Goforth et al, 1983)

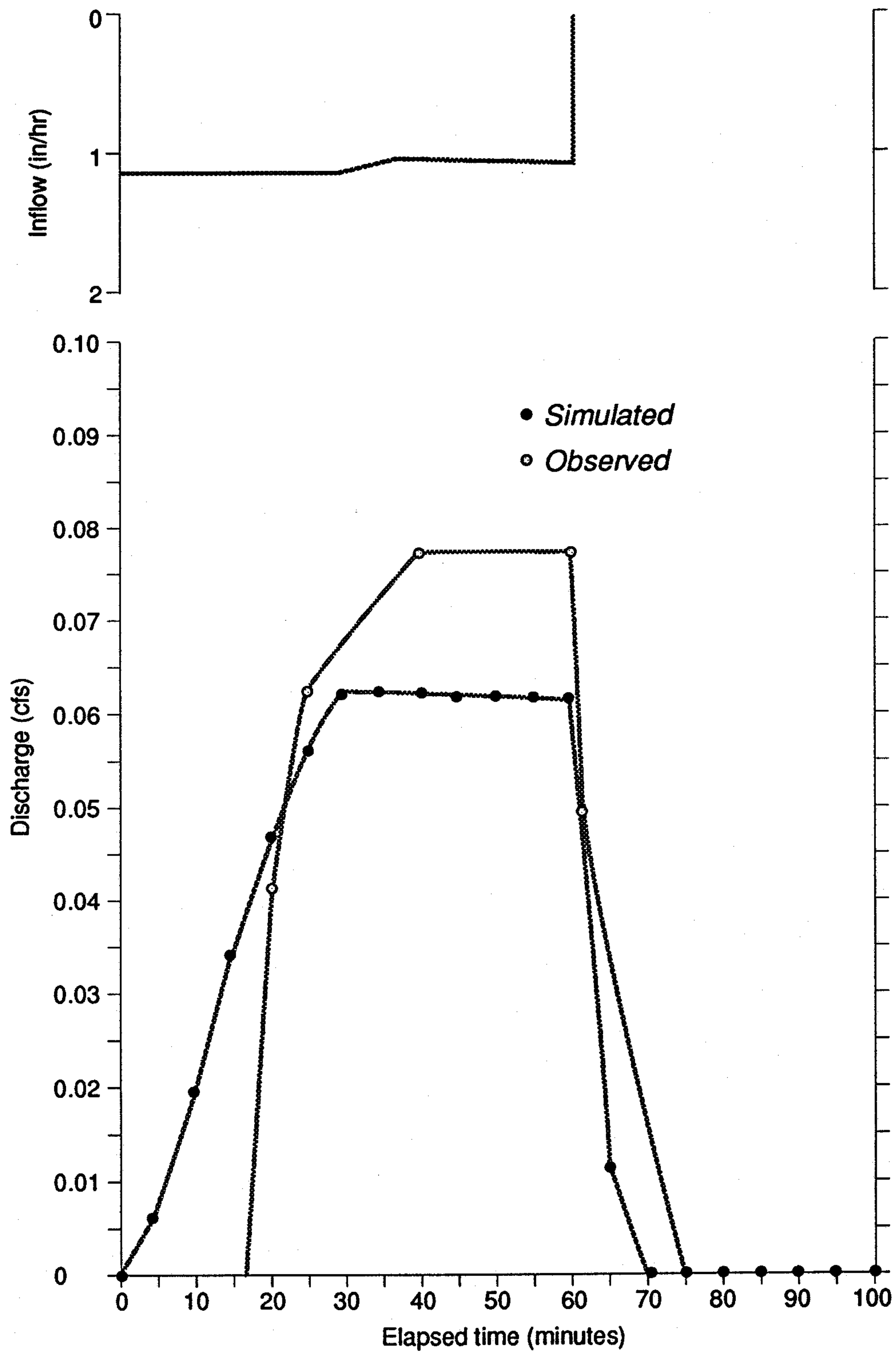
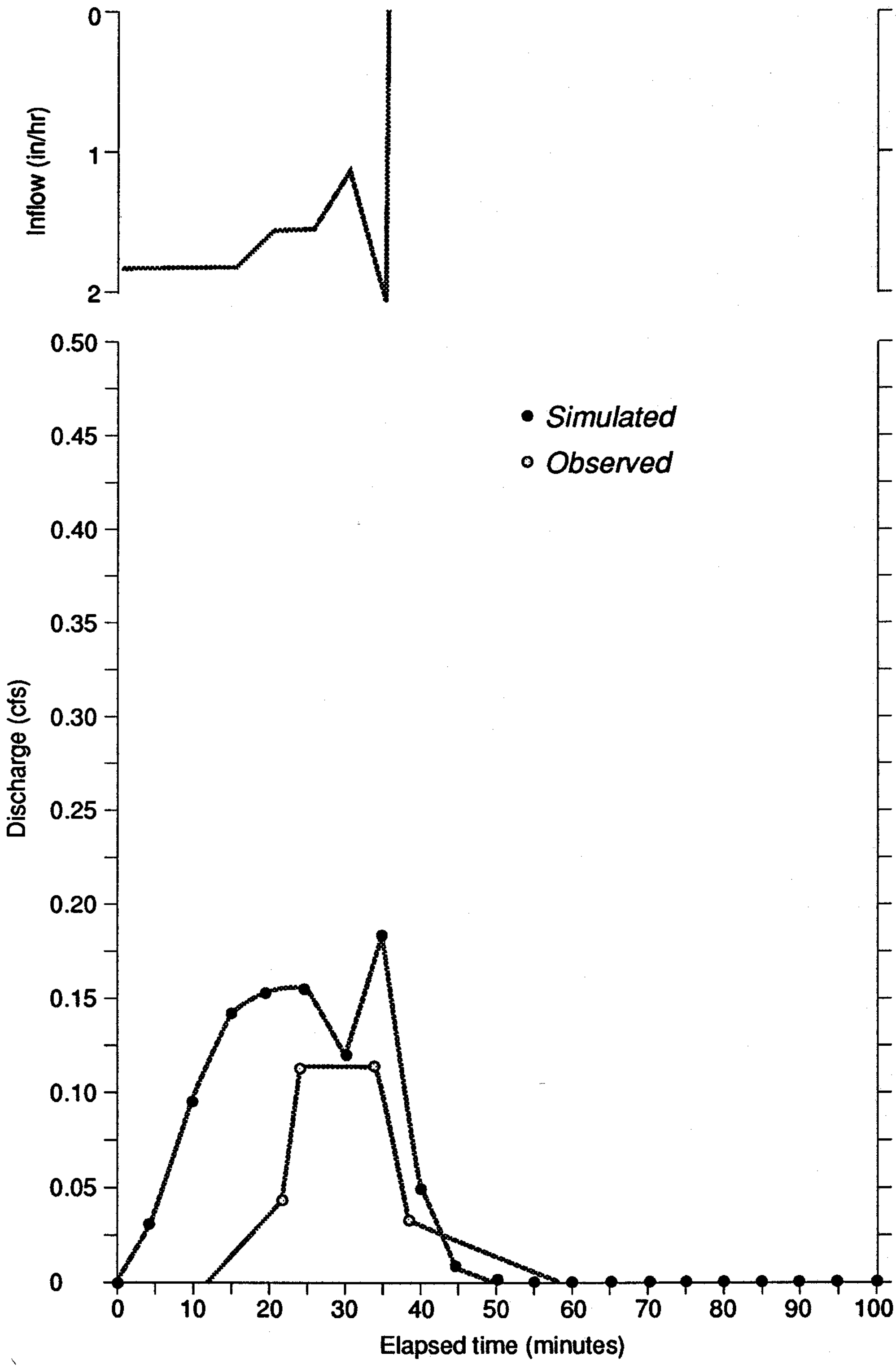


Fig 20 Lattice block pavement – simulated/observed runoff hydrographs for storm event of 11/3/1982 (Goforth et al, 1983)



PGH/21/4-91/LO

Fig 21 Lattice block pavement – simulated/observed runoff hydrogaphs for storm event of 18/3/1982 (Goforth et al, 1983)

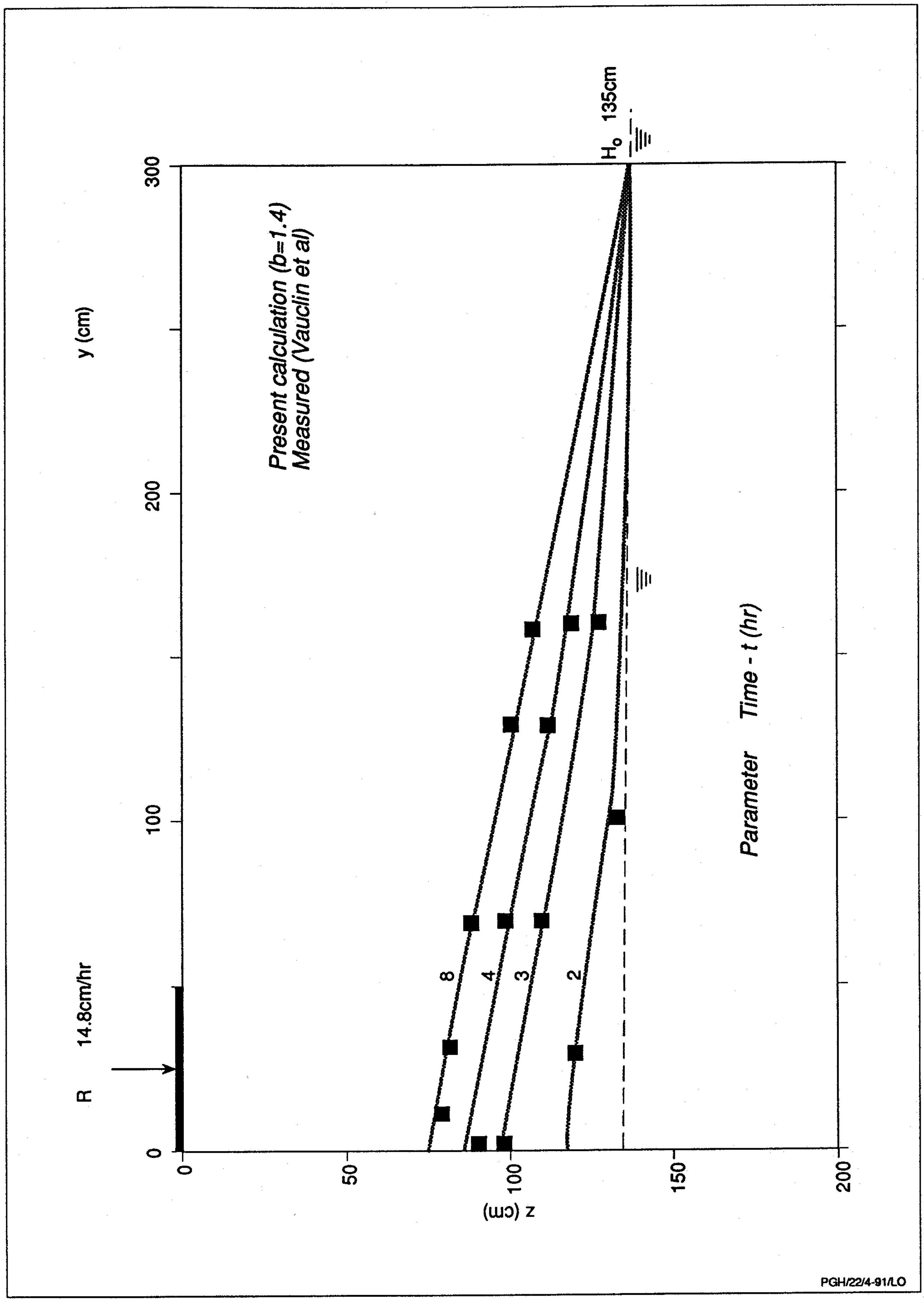
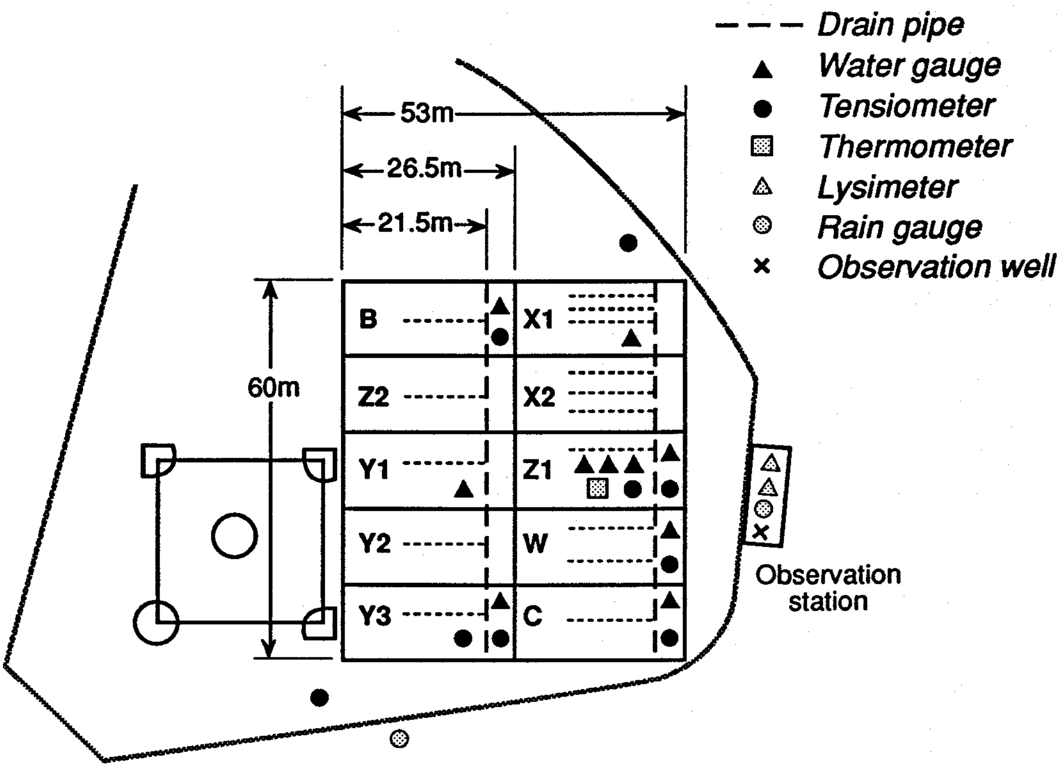
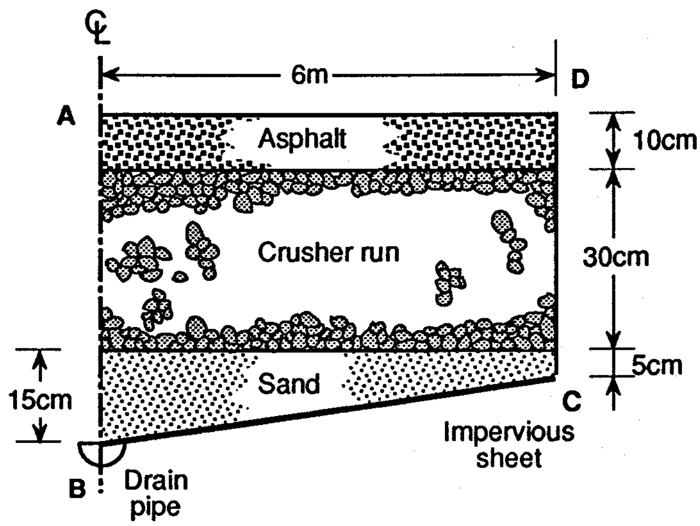


Fig 22 Simulation of two dimensional unsaturated seepage (Tamai et al, 1987)



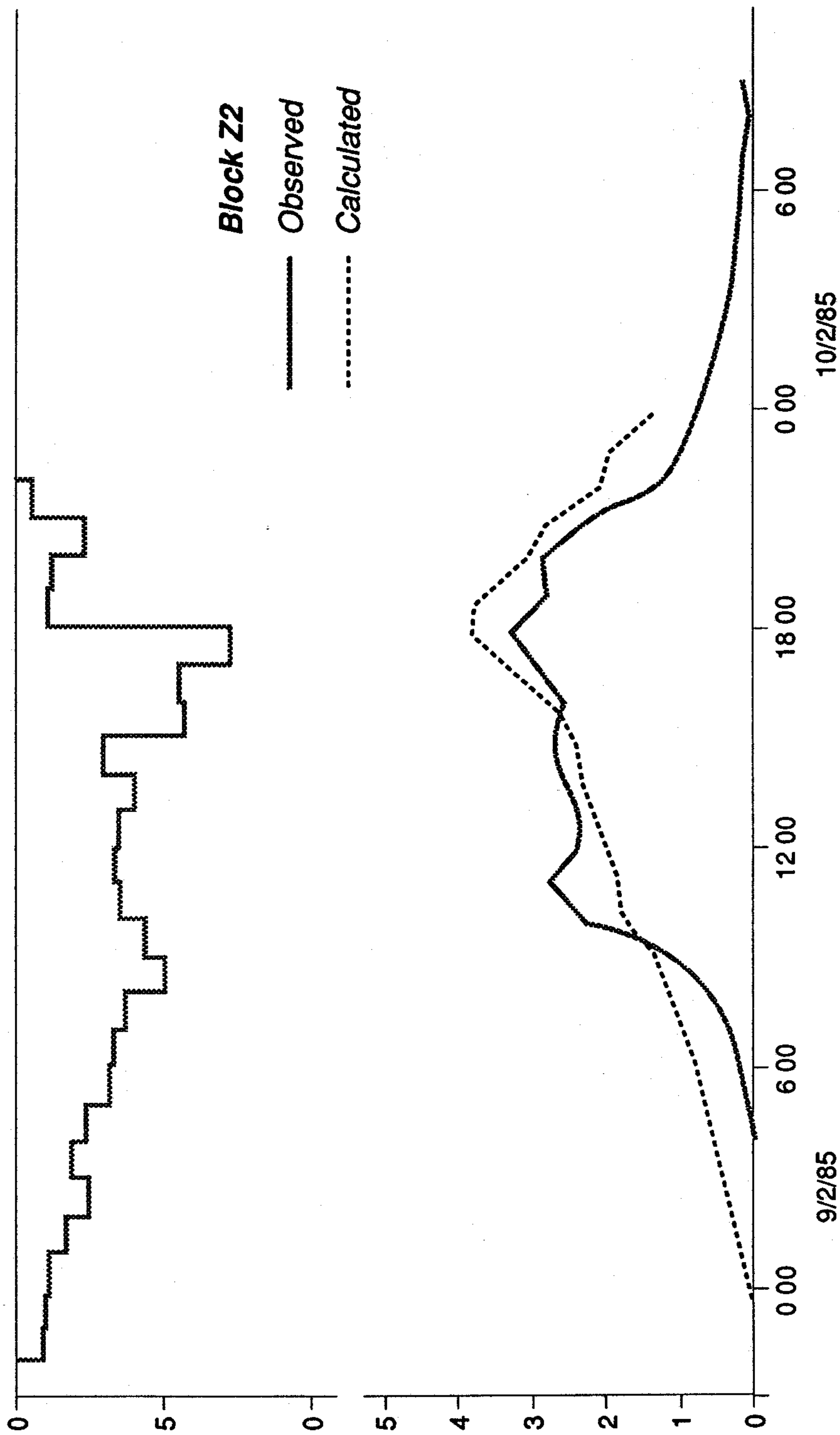
Plan of the observation field



Vertical section of block Z2

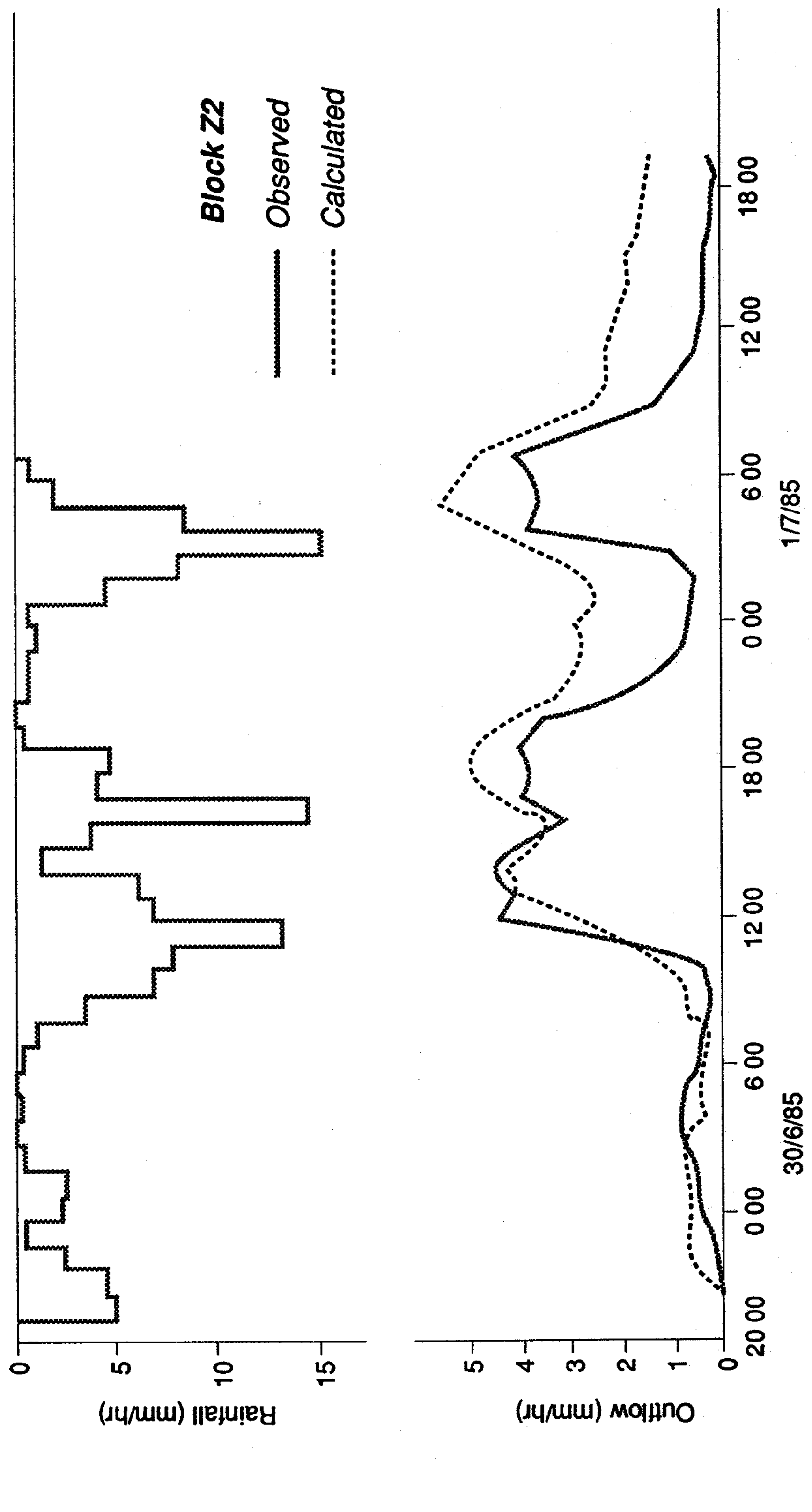
PGH/23/4-91/LO

Fig 23 Pervious asphalt pavement experimental site – University of Tokyo (Tamai et al, 1987)



PGH/24/4-91/LO

Fig 24 Pervious asphalt pavement – simulated/observed runoff hydrographs for storm event of 9/2/1985 (Tamai et al, 1987)



PGH/25/4-91/LO

Fig 25 Pervious asphalt pavement – simulated/observed runoff hydrographs for storm event of 30/6/1985, clogged drainage pipe (Tamai et al, 1987)

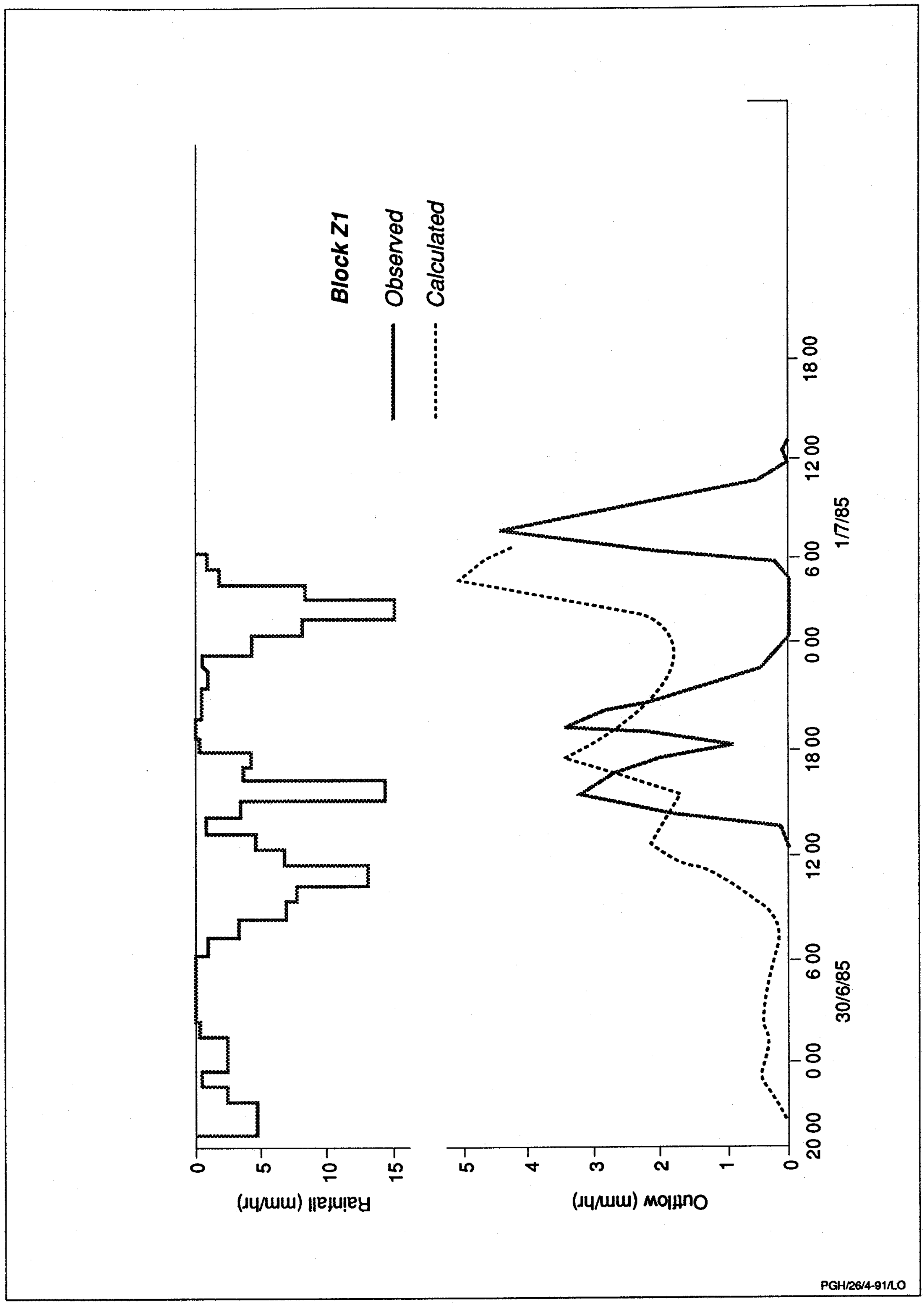


Fig 26 Pervious asphalt pavement – simulated/observed runoff hydrographs for storm event of 30/6/1985, natural subsoil base (Tamai et al, 1987)

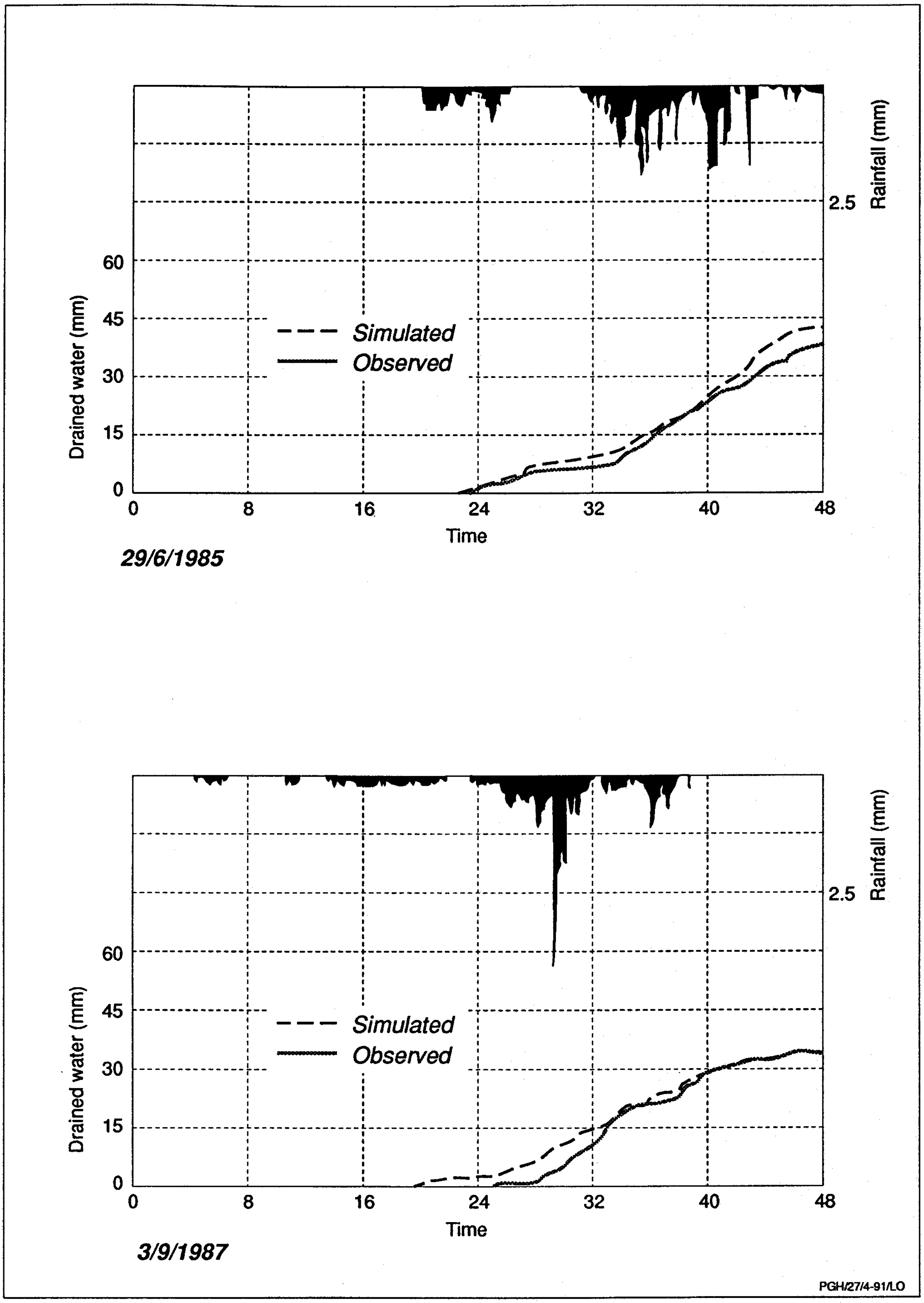


Fig 27 Pervious asphalt pavement – simulated/observed runoff hydrographs neglecting hydraulic conductivity/negative pressure hysteresis effects (Itchikawa and Harada, 1990)

APPENDICES

APPENDIX 1

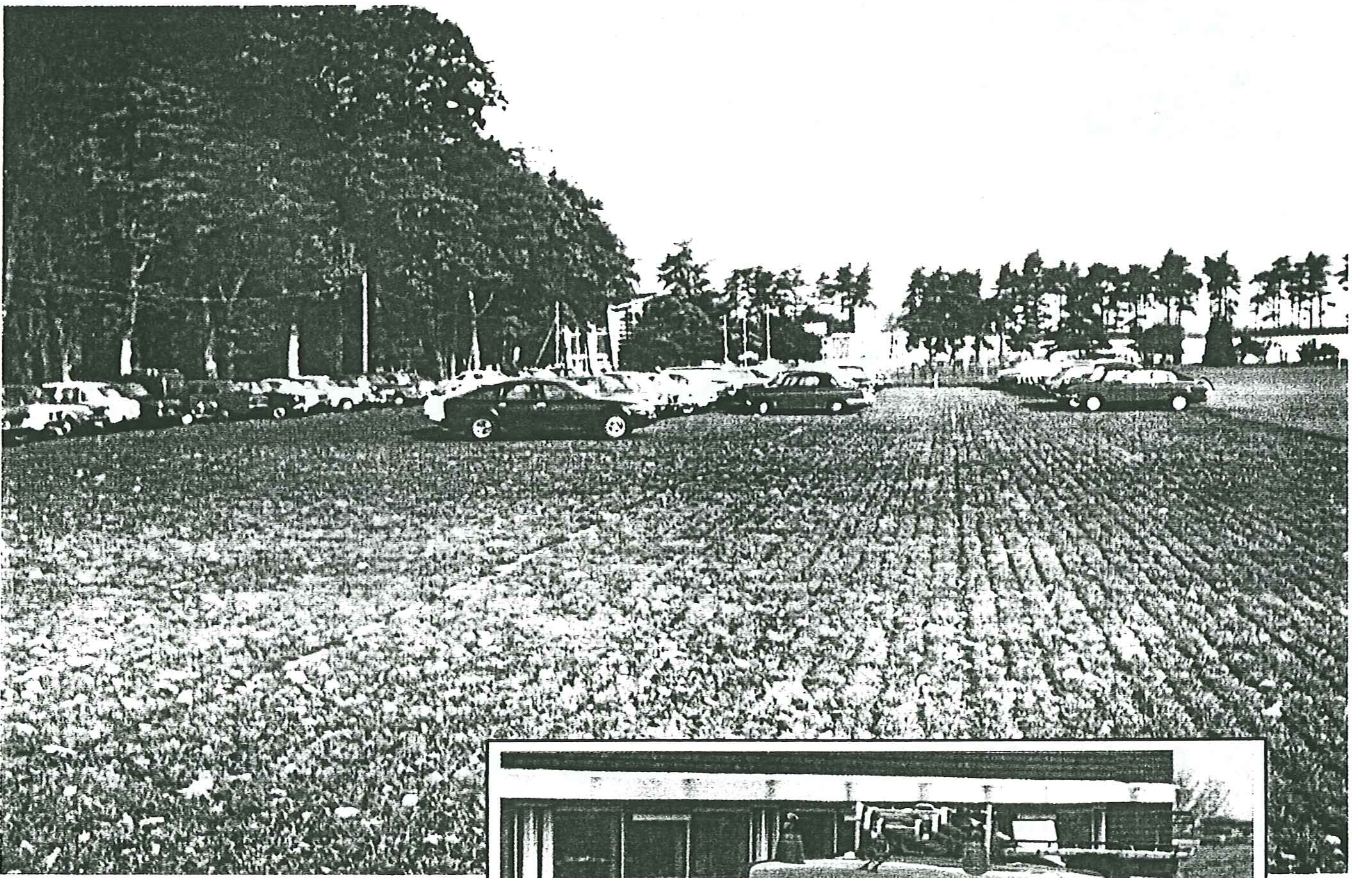
Proprietary permeable pavement block systems
available in the United Kingdom.

GRASSCRETE

Grass
Concrete
Limited

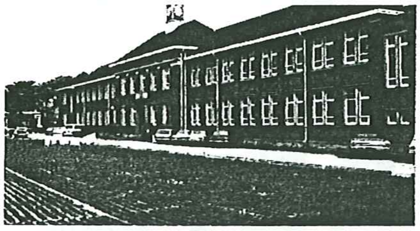
GRASSCRETE®

The only insitu grass and concrete surface in the world



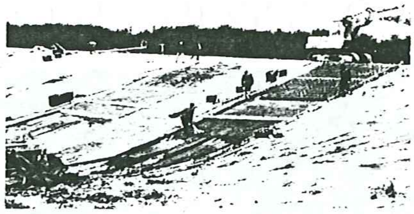
CI/SfB		
90	(4-)	Eq
GOOD ENVIRONMENT		

GRASSCRETE Features

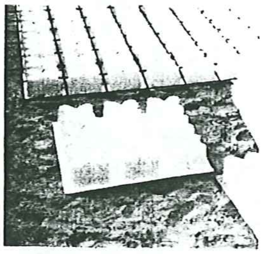


GRASSCRETE is an insitu process to produce a surface with the general appearance of natural grass and the loadbearing capacity and durability of continuously reinforced concrete. GRASSCRETE is suitable for carrying vehicular loads up to 40 tonnes and provides a well drained surface. GRASSCRETE is the only grass and concrete surface to offer the superior properties of continuously reinforced concrete.

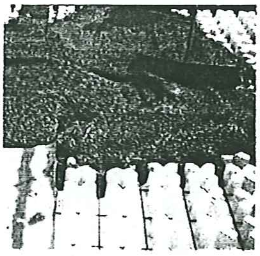
GRASSCRETE has been approved by leading Fire Authorities and has solved the problem of providing the ideal surface for fire paths and service roads to hospitals and multi-storey buildings, by giving emergency access for fire appliances in landscaped areas. Other uses for GRASSCRETE are urban and rural car parks, verge parking, hardstanding areas, country parks, laybys, housing estate parking, caravan parks and General Improvement Areas.



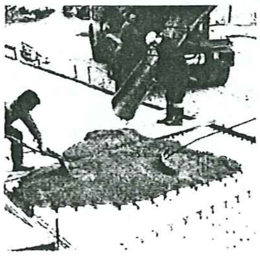
GRASSCRETE Laying



Place GRASSCRETE formers on a well compacted sub-base with 10-20mm sand blind used for levelling.



Reinforcing steel mesh is laid in position on pre-formed spaces provided within each former.



Pour concrete onto boards. Screed level with top of formers. Remove latent concrete to leave the tops of the formers exposed.

GRASSCRETE Specifications

STANDARD SPECIFICATION – GRASSCRETE SURFACING

Grasscrete formers type GC   mm deep laid on a consolidated sub-base with a 10/20mm blinding layer of sand. Steel mesh reinforcement to BS4483 reference
A   weighing   kg/m²
Concrete 28 MN/m² at 28 days with an added air entrainment of 3%, 10mm maximum aggregate and a slump of 125mm placed around formers and mesh. Level surface, burn out exposed tops of formers and fill with fine friable topsoil. After settlement top up to required level with fine friable topsoil. Sow GRASSMIX NO.   at a rate of 50g/m², fertilize as necessary.

N.B. Mix design may vary subject to local materials.

NOTES

1. Minimum consolidated sub-base recommended 100mm deep.
2. Expansion joints are recommended at 10 metre intervals.
3. Dowelled joints can be used on areas subject to frequent heavy loadings to obtain maximum load transfer.
4. A solid concrete edge minimum 100mm wide must be provided to the perimeter of a GRASSCRETE area and to every constructional joint.

Full information in connection with the laying of GRASSCRETE is detailed in the manual "A Guide to the Laying of GRASSCRETE".

All in accordance with the manufacturers' instructions GRASS CONCRETE LTD., WALKER HOUSE, 22 BOND STREET, WAKEFIELD WF1 2QP. (0924) 375997.

GRASS – SPECIFICATION

	Mix No. 1	Mix No. 2	Mix No. 3
Chewings Fescue	40%	40%	15%
Creeping Red Fescue		40%	30%
Smooth Stalked Meadow Grass	10%	10%	10%
Browntop Bent		10%	
Crested Dogstail			5%
Perennial Ryegrass	50%		40%

GRASS-MIX No. 1

Fine leaved grass mixture recommended for car parks.

GRASS-MIX No. 2

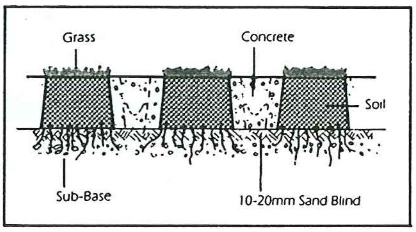
A low maintenance grass mix recommended for fire and emergency access.

GRASS-MIX No. 3

A low maintenance grass mix recommended for embankments.

PLEASE CONTACT US FOR OUR COMPLETE SUPPLY AND LAY SERVICE TEL: (0

RASSCRETE is the answer to the problem of oviding embankment stabilization in rural eas. The reinforced concrete guarantees otection against erosion and settlement d the grass ensures compatibility with the jacent landscape. GRASSCRETE has been ed on spillways, balancing lakes, river and servoir embankments.

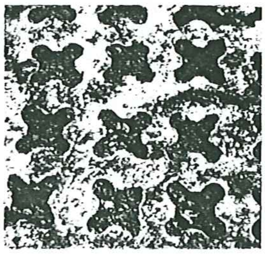


An important advantage of GRASSCRETE is its self-draining properties. The specially designed holes in a GRASSCRETE surface have the unique benefit of providing a greater area at the base, so preventing compaction of the soil and ensuring the maximum rate of perculation. The natural drainage of surface water to the sub-base reduces and can eliminate the need for expensive drainage systems.

exibility is an important feature of RASSCRETE and is clearly shown in this otograph. Here GRASSCRETE is being laid the inclined face of a dam, following the tural gradients and contours on site.

The object of GRASSCRETE is to create an overall appearance of grass. The use of grass mixtures that encourage rapid establishment of root growth, and create a healthy and attractive grass cover, are very important.

After 48 hours, burn away exposed former tops.



Fill voids with good quality fine friable top soil.

After settlement, seed and top up with soil using the correct grass for the contract.

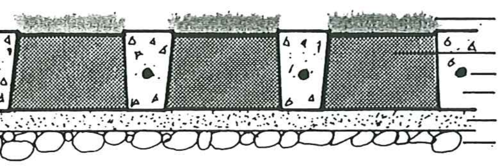
Fertilize as for normal grass surfaces.

GRASSCRETE Data

CI FORMER

0 x 600 x 100mm deep rmers/m^2=2.78

Concrete/m^3=15m^2
Soil/m^3=18m^2



C2 FORMER

0 x 600 x 150mm deep rmers/m^2=2.78

Concrete/m^3=11m^2
Soil/m^3=12m^3

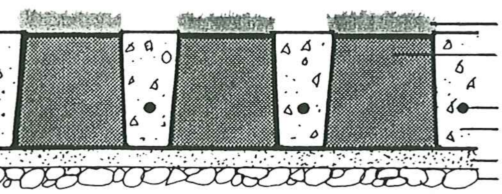
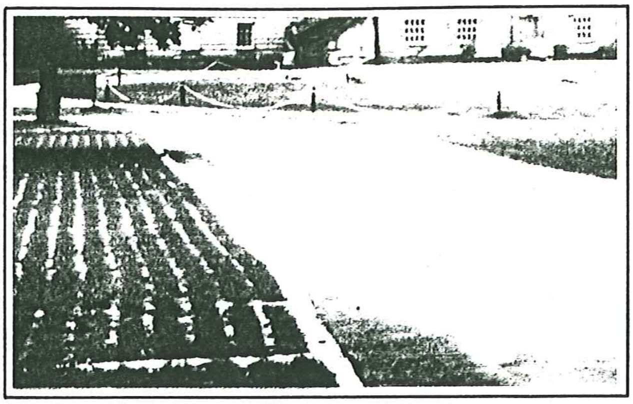


TABLE 1. SUGGESTED DESIGN CRITERIA WHEN SPECIFYING GRASSCRETE

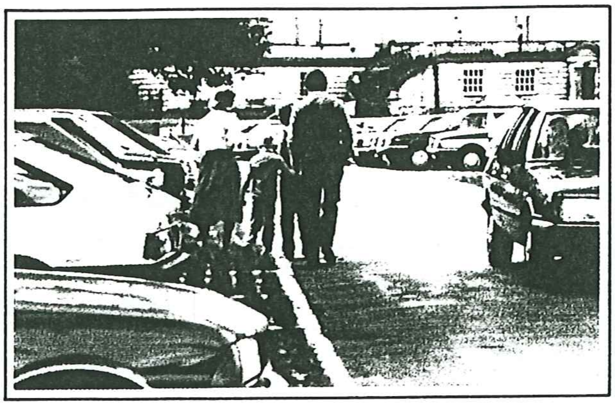
APPLICATION	LOADING	SUB-BASE	GRASSCRETE	MESH REINFORCEMENT
Private Cars Light Commercial Vehicular Traffic	Up to 10 Tonnes	100mm	GC1 100mm	A193 (3.02 kg/m^2)
Fire Access (low rise) Service Roads	Up to 10 Tonnes	150mm	GC1 100mm	A193 (3.02 kg/m^2)
Fire Access (multi-storey) Heavy Traffic	Up to 40 Tonnes	150mm	GC2 150mm	A252 (3.95 kg/m^2)
Embankment Stabilization Slope Protection (medium water flows) Amenity Water Developments	——	Optional	GC1 100mm	A193 (3.02 kg/m^2)
Embankment Stabilization Spillways, Flood Control, Slope Protection (heavy water flows)	——	Optional	GC2 150mm	A252 (3.95 kg/m^2)

This table is provided as a guide only. Conditions on site do vary and may therefore require changes in the sub-base, reinforcement and depth of GRASSCRETE.
Consideration should be given to ensuring that the sub-base is capable of withstanding the load of laden concrete vehicles during laying of the Grasscrete surface.

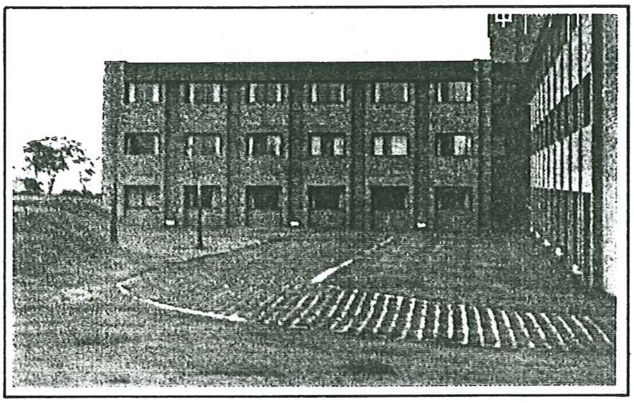
Information is given in good faith, without warranty, and subject to alteration without prior notice.



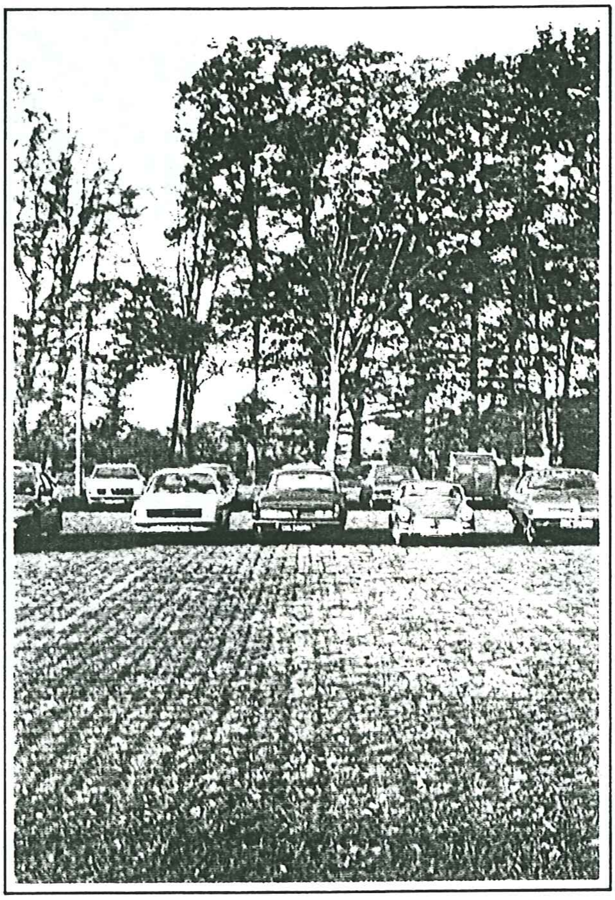
Verge parking without traffic



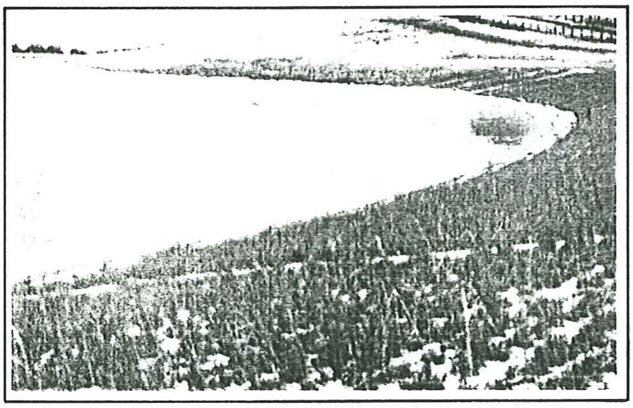
Verge parking with traffic



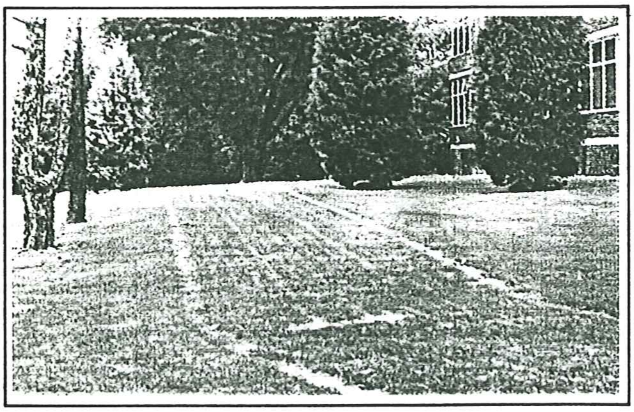
Fire access hotel



Environmental car parking – rural area



Embankment protection – reservoir



Emergency access – office block

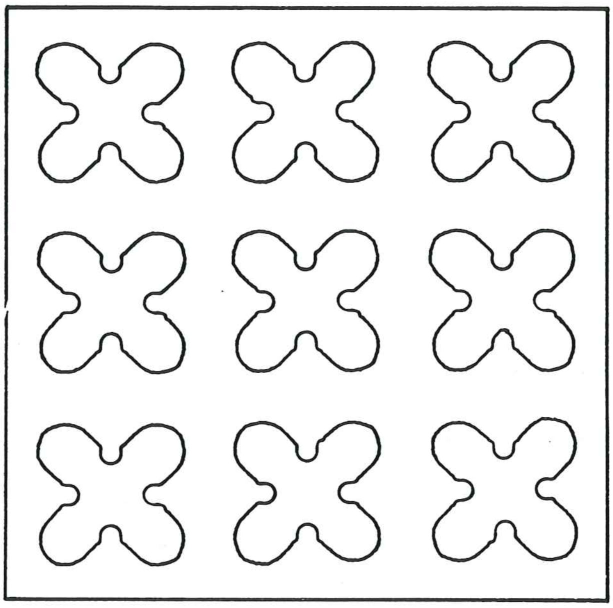
Grass Concrete Limited
Grass Concrete International Limited
Walker House, 22 Bond Street, Wakefield,
West Yorkshire, WF1 2QP.
Telephone (0924) 374818/375997
Telex 51458 Comhud G for
Grassconcrete.

FAX No. 0924 290289

Brochures with French, German and Flemish text are available on request

FOR PRECAST GRASSBLOCK BROCHURE CONTACT WAKEFIELD

STANDARD SPECIFICATION
GRASSCRETE GC3 76mm DEEP

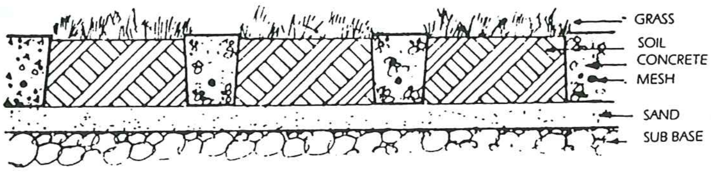


GC3 FORMER

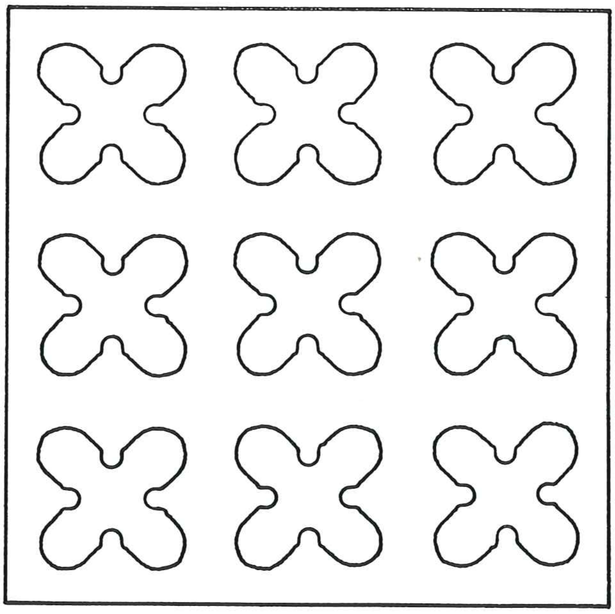
600 x 600 x 76mm deep   Concrete/m^3 = 22m^2
Formers/m^2 = 2.78   Soil/m^3 = 24m^2

SPECIFICATION

Grasscrete formers type GC3 76mm deep laid on a consolidated sub-base with a 10/20mm blinding layer of sand. Steel mesh reinforcement to BS4483 reference A142 weighing 2.22kg/m^2. Concrete 28 MN/m^2 at 28 days with an added air entrainment of 3%, 10mm maximum aggregate and a slump of 125mm placed around formers and mesh. Level surface, burn out exposed tops of formers and fill with soil. After settlement sow GRASSMIX No. 1 at a rate of 50g/m^2 and top up with fine friable topsoil, apply fertilizer as necessary.



STANDARD SPECIFICATION
GRASSCRETE SD76 76mm DEEP

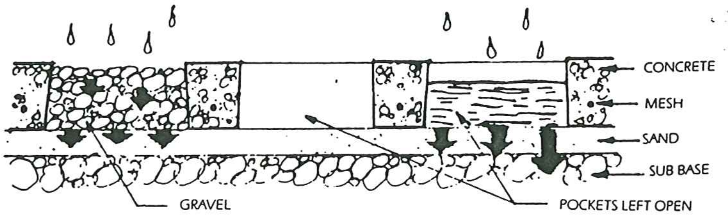


SD76 FORMER

600 x 600 x 76mm deep   Concrete/m^3 = 22m^2
Formers/m^2 = 2.78

SPECIFICATION

Grasscrete formers type SD76 76mm deep laid on a consolidated sub-base with a 10/20mm blinding layer of sand. Steel mesh reinforcement to BS4483 reference A142 weighing 2.22kg/m^2. Concrete 28 MN/m^2 at 28 days with an added air entrainment of 3%, 10mm maximum aggregate and a slump of 125mm placed around formers and mesh. Level surface, burn out exposed tops of formers. Pockets may be filled with 20-5mm down gravel or left open for maximum drainage.



Grass Concrete Limited

All in accordance with the manufacturers instructions

WALKER HOUSE, 22 BOND STREET,
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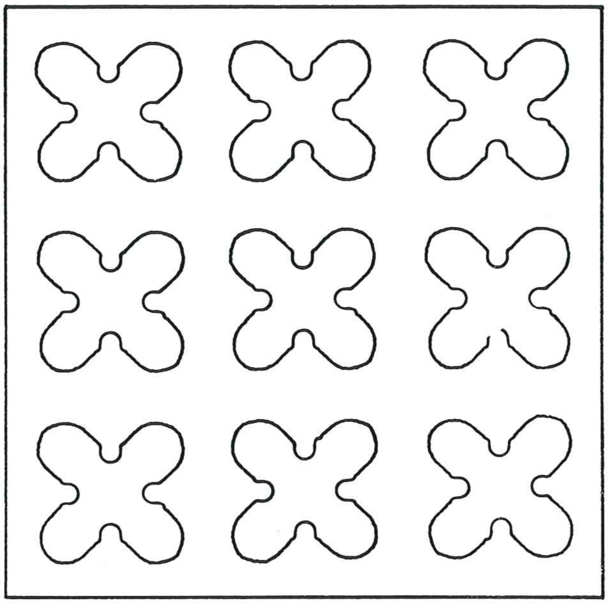
TELEPHONE: WAKEFIELD (0924) 375997/374818
TELEX: 51458 COMHUD G FOR GRASSCONCRETE
FAX: (0924) 290289

(Method of measurement overleaf)

STANDARD SPECIFICATION
GRASSCRETE GC1 100mm DEEP



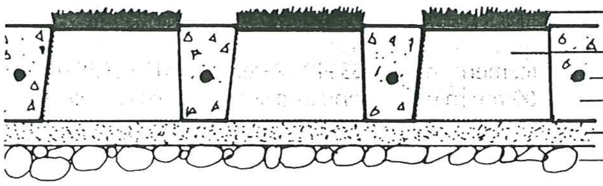
GC1 FORMER

600 x 600 x 100mm deep
Formers/m^2 = 2.78

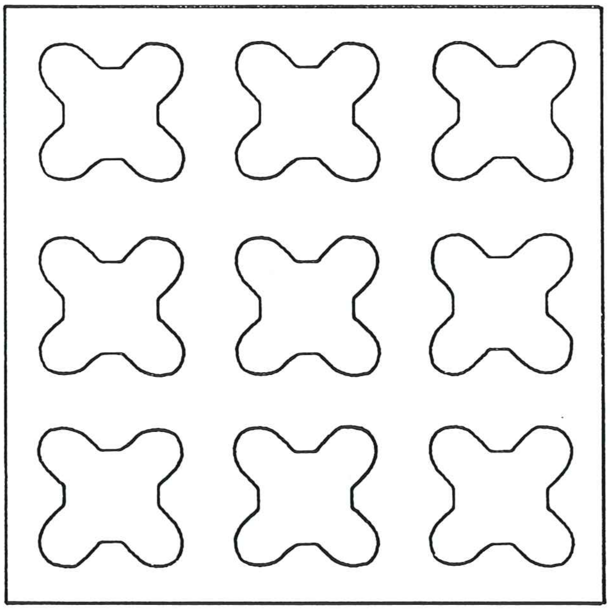
Concrete/m^3 = $15m^2$
Soil/m^3 = $18m^2$

SPECIFICATION

Grasscrete formers type GC1 100mm deep laid on a consolidated sub-base with a 10/20mm blinding layer of sand. Steel mesh reinforcement to BS4483 reference A193 weighing $3.02kg/m^2$. Concrete 28 MN/m^2 at 28 days with an added air entrainment of 3%, 10mm maximum aggregate and a slump of 125mm placed around formers and mesh. Level surface, burn out exposed tops of formers and fill with soil. After settlement sow GRASSMIX No. 1 at a rate of $50g/m^2$ and top up with fine friable topsoil, apply fertilizer as necessary.



STANDARD SPECIFICATION
GRASSCRETE GC2 150mm DEEP



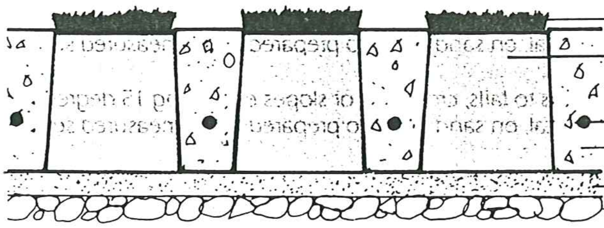
GC2 FORMER

600 x 600 x 150mm deep
Formers/m^2 = 2.78

Concrete/m^3 = $11m^2$
Soil/m^3 = $12m^2$

SPECIFICATION

Grasscrete formers type GC2 150mm deep laid on a consolidated sub-base with a 10/20mm blinding layer of sand. Steel mesh reinforcement to BS4483 reference A252 weighing $3.95kg/m^2$. Concrete 28 MN/m^2 at 28 days with an added air entrainment of 3%, 10mm maximum aggregate and a slump of 125mm placed around formers and mesh. Level surface, burn out exposed tops of formers and fill with soil. After settlement sow GRASSMIX No. 2 at a rate of $50g/m^3$ and top up with fine friable topsoil, apply fertilizer as necessary.



Grass Concrete Limited

All in accordance with the manufacturers instructions

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FAX: (0924) 290289*

(Method of measurement overleaf)

GRASSCEL

CI/SfB (90.4) Ff2

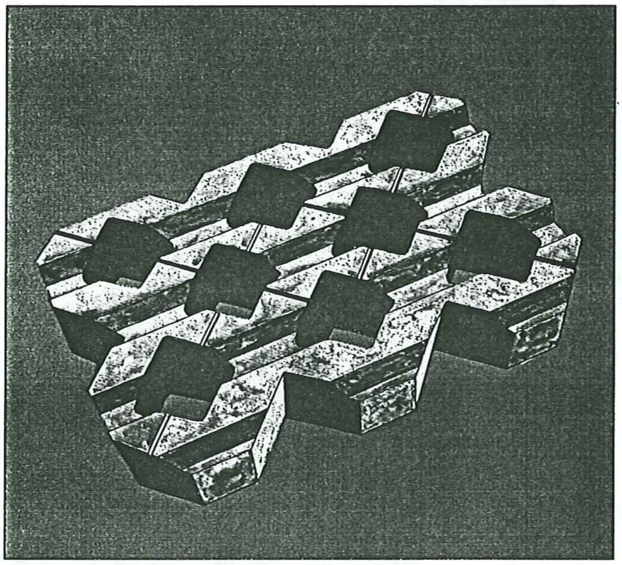
Grasscel

Tarmac Masonry Products

Grasscel

Combines all the strength and durability of concrete with the natural beauty of grass

Unsightly open surfaced areas are now a thing of the past – Grasscel has seen to that. The unique design of Grasscel combines the strength and durability of concrete with the natural appearance of grass, to give a really hard working surface area that looks natural and blends beautifully with the environment.



A natural for parking

The practical, hard concrete surface of Grasscel makes it a natural choice for car parks and access areas. Grasscel has been designed to carry both pedestrian and vehicular traffic (light and heavy) and is ideal for car parks, lorry parks, precinct and amenity areas, hard standings, firepaths and other emergency access throughways.

Easy dry laying

Unlike most conventional methods of surfacing, Grasscel is dry laid. Skill levels and plant requirement are minimal.

Attractive and practical

The unique design of Grasscel ensures extensive vegetation growth to provide an attractive surface area consisting of approximately 75% grass and 25% concrete. This is not only aesthetically pleasing to the environment but has the practical advantage of helping to reduce problems of waterlogging and surface drainage. Providing the infill soil and sub-base are of average permeability, surface water will readily soak away.

Cost-effective

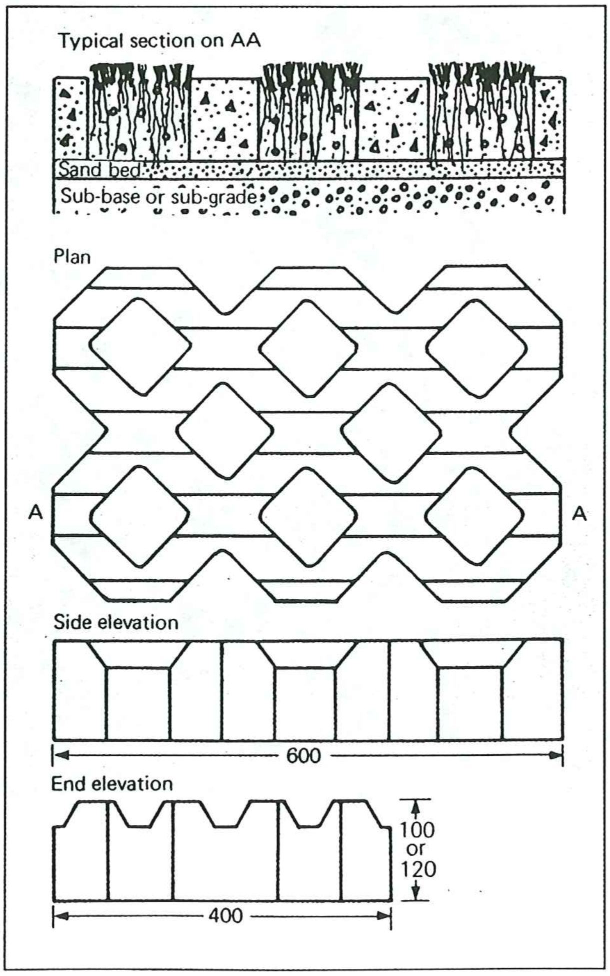
The durability, practical good looks and easy laying technique add up to a really cost-effective system that compares favourably with conventional surfacing methods – that's Grasscel, the concrete surface that grows on you.

Specification

Grasscel units consist of cavity-forming interconnecting concrete bars with localised upstands for wheel contact at the surface. The cavities and channels are filled in with soil, and grass is sown, resulting in a surface consisting approximately of 75% grass and only 25% concrete. There is just one component, manufactured from high quality concrete to ensure long term durability.

Grasscel units are based on a modular grid of 600 x 400mm and units are available in 100 or 120mm thickness.

Weight per unit: 100mm thickness approx 29 kg.
120mm thickness approx 35 kg.
Number per sq. m = 4.16
Top soil requirements = 100mm thickness approx 0.8 tonne per 10 sq. m of area
120mm thickness approx 1.0 tonne per 10 sq. m of area



Technical information

Recommended construction for Grasscel.

The Grasscel system consists of three main elements:

1) a free draining sub-base (granular material, hardcore, hoggin, etc.)
2) a 20mm thick laying course of sharp sand.
3) 100 or 120mm thick Grasscel units infilled with soil and grass.

In common with any other form of surfacing, the selection and construction of the sub-base is the key to achieving a stable load bearing surface.

Local site conditions may frequently eliminate the need for a new sub-base, where the Grasscel is to be used by light vehicles or pedestrians.

For heavy vehicular use, or unstable ground conditions, advice should be sought from a local engineer or reference made to Road Note 29 'A Guide to the Structural Design for New Roads' (HMSO 1970).

Grass seed mixture

The type of grass can be any mixture suitable to the local environment and to the use of the area. When in doubt a local seed merchant should be consulted. However, as a general recommendation the following mixture has been selected for its colour retention and also its wear and drought resistant properties:

Creeping Red Fescue 60%. Poa Pratensis 30%. Brown Top 5%. Poa Trivalis 5%.

This seed mixture, tested in accordance with the provisions of the 1920 Seed Act Regulations, should be sown at a rate of 42.5g per sq. m.

Other uses – embankments

Grasscel can also be used for the protection and surface stabilisation of embankments in both wet and dry situations. Although Grasscel can be laid to any angle it is generally limited to slopes not exceeding the natural angle of repose of the underlying material.

As the product is designed to give surface protection and not structural support the bank must remain stable at the proposed slope, thus generally limiting the maximum angle to 40° – 50°.

An adequate support should be constructed at the toe of the slope, the design of which will depend on the proposed angle and length of protection, also ground conditions at the toe. Where additional support is considered desirable wooden stakes can be driven into the bank through the block cavities. The bank surface should be graded to the required shape and where necessary regulated to correct lines and levels with a nominal 50mm thick layer of quarry scalping type material, suggested grading 20mm to dust.

Grasscel blocks should then be laid dry jointed with their long axis running along the bank, each successive course being laid to a stretcher bond whilst ensuring correct matching of block pattern.

Where the passage of ground water is likely to cause leaching from the sub-strata a suitable filter membrane should be laid directly beneath the Grasscel protection.

When laying is completed the cavities can be filled with top soil and the area seeded, or alternatively in frequently wet situations the cavities can be filled with a granulated material.

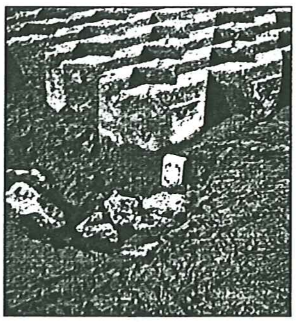
If the top of the embankment is likely to be used by vehicular traffic the sub-base selection and construction should be based on the vehicular use recommendations as given elsewhere.

Where it is necessary to cut blocks as on curved surfaces this can easily be achieved with the aid of a carborundum disc cutter. Further information is available on request in respect of suggested layouts to sloping curved surfaces.

Laying Grasscel

Sub-base, laying course and wearing course

a) Lay the sub-base, compact by using a vibrator roller or tamping and blind the surface to achieve a smooth, even finish. (An ideally compacted sub-base will permit a person to stand on it without leaving any footprints).
b) If the perimeter line of the sub-base is unrestrained, it should be extended by at least 300mm beyond the finished edge of the Grasscel.
c) A laying course formed from sharp sand (0-5mm grain size) is placed on the sub-base and screeded and levelled to a thickness of 20mm. Prior to laying the Grasscel, the sand should be lightly compacted using a tamping board.
d) Wearing course: place the Grasscel units, edge to edge, onto the prepared sand bed.
e) The units should be consolidated into position by using a wooden tamping board.



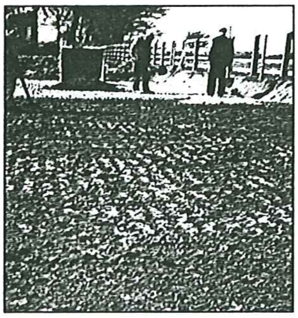
Soiling and seeding

a) Fill the voids and channels with a clean, good quality top soil.
b) Level off 100mm below the top surface, using a stiff broom, and sow the grass seed.

c) If required, apply a suitable root promoting fertilizer.
d) Add a further 10mm layer of fine soil and level off to the top surface.

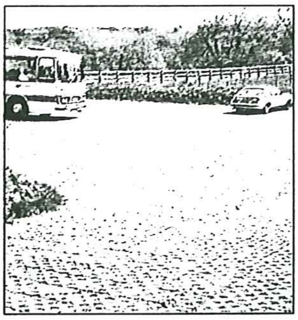
N.B. The effects of watering or rainfall will naturally cause the infill soil to settle by up to 12mm below the upper surface. Any excess settlement should be topped up by the addition of a further layer of soil.

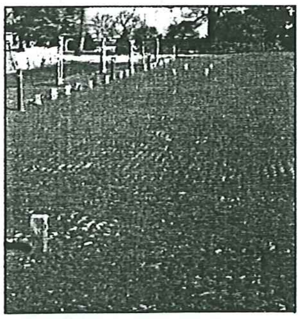
An alternative method, preferred by some users of Grasscel where wheeled site traffic can be relied upon to travel over the Grasscel area, is to overfill with topsoil by 50mm. Compaction of the soil into the voids and channels will be achieved by wheeled site traffic and the last job on site will be to level off the topsoil and sow the grass seed as above. If good compaction has been ensured, further topping up should be unnecessary.



Maintenance and mowing

a) Grasscel is ready for vehicular traffic as soon as it is laid.
b) Once the grass has been sown, new laid Grasscel should be treated as any other normal area of grass and twice a year (preferably early spring or summer), a suitable top dressing fertilizer should be applied. Although the mowing procedure is the same as for ordinary grass, it is advisable to take the cuts diagonally across the top of the units.





Other concrete ideas for today's environment

Quickpave – interlocking paving for roads, drives, paths, car and lorry parks.

Kriblok – crib walling systems. Dry-laid economical crib walling with a pleasing appearance.

Dytap – revetment systems for protection of embankments on waterways, reservoirs and coast.

Flagreca – concrete masonry made 'anyway you want it' to suit the individual project.

Quikkova – sectional concrete inspection chambers.

Kiosks – A wide variety of strong, secure structures available in exposed aggregate or plain finishes.

SALES OFFICES

Tarmac Masonry Products Limited.

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  Grange Road, Houstoun Industrial Estate,
  Livingston, West Lothian EH54 5DJ.
  Telephone: 0506 32524. Fax: 0506 33666.

- 2. Barrasford
  Northumberland Concrete Factory
  Barrasford Quarry, Barrasford, Hexham,
  Northumberland NE48 4AP.
  Telephone: 0434 681495. Fax: 0434 681473.

- 3. Stainton
  Stainton Stone,
  Stainton Quarry, Stainton, Barnard Castle,
  Co. Durham DL12 8RB.
  Telephone: 0833 690444. Fax: 0833 690377.

- 4. Cawdor
  Cawdor Works
  Snitterton Road, Matlock, Derbyshire.
  Telephone: 0629 56677.

- 5. Ruthin
  Brooklyns Factory
  Quarryfields, Ruthin, Clwyd LL15 2UG
  Telephone: 08242 2493. Fax: 08242 4527.

- 6. Coleford
  Rebastone Factory
  Newbury Works, Coleford, Bath BA3 5RX.
  Telephone: 0373 812444. Fax: 0373 813266.

- 7. Bath
  Rebastone Factory
  Mount Pleasant Quarry, Shaft Road,
  Combe Down, Bath BA2 7HP.
  Telephone: 0225 833586. Fax: 0225 835950.

- 8. Taunton
  5 North Street, Taunton, Somerset TA1 1LH.
  Telephone: 0823 251451. Fax: 0823 335163.

- 9. Wareham
  Brooklyns Factory,
  Sandford Lane, Wareham,
  Dorset BH20 4DY.
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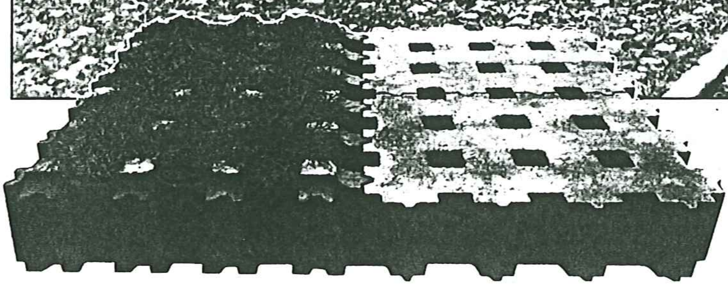
Tarmac Masonry Products

Tarmac
Building Materials

GRASSGRID

CI/SfB | | (90.4) | Ff2 | |
May 1989

CHARCON
GRASSGRID



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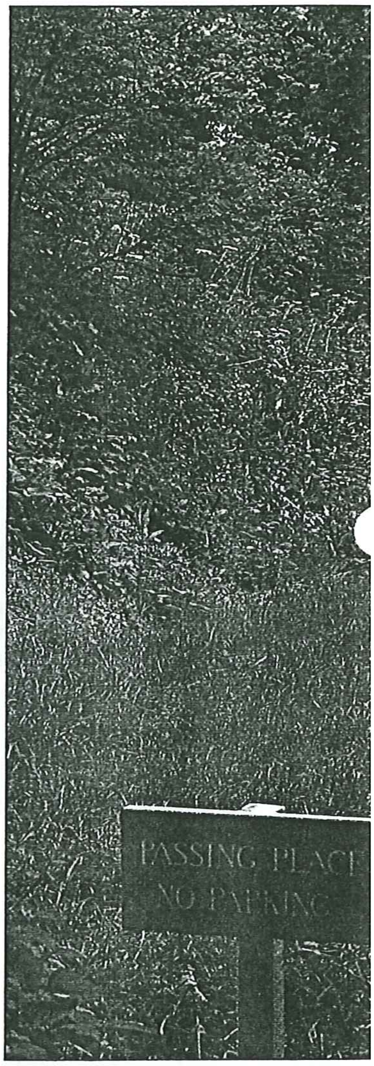


Grassgrid provides the answer to the toughest brief in landscaping: a system that works and lasts like concrete, but does not look like concrete.

Once established and planted, Grassgrid quickly lives up to its name.

The system is made up of interlocking units, strong enough to take any roadgoing vehicle, but honeycombed with cavities large enough for grass to seed and grow with little encouragement.

Just 15% of the surface area is concrete: the remaining 85% is available for grass cover – but not only grass. By substituting variegated chippings, gravel or loose stones, Grassgrid can change its appearance to suit the application.

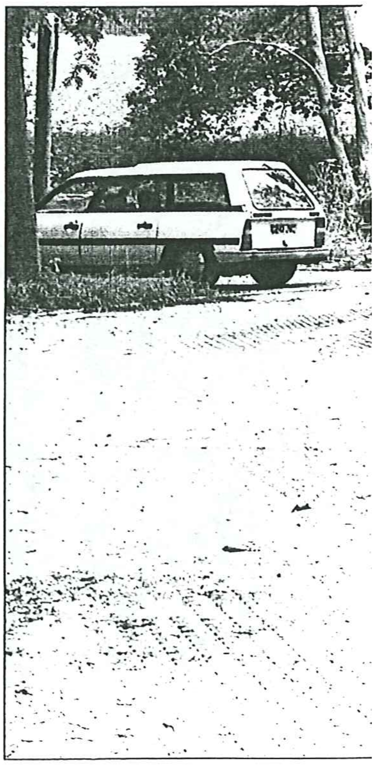
Grassgrid is the ultimate in versatile good looks.

Two Sides to the Story

Excellent drainage is inherent in the design, as is highly efficient weight distribution – which explains how the practical necessity of concrete can be reconciled with the aesthetic appeal of grass.

But that is only one side of the story.

Grassgrid's cavities are designed like inverted pyramids so that when units are laid upside down the percentages are reversed. In effect 85% concrete can be laid next to 85% grass, the flat self draining surface being ideal for a cycle path or walkway to preserve the lawn beside it.



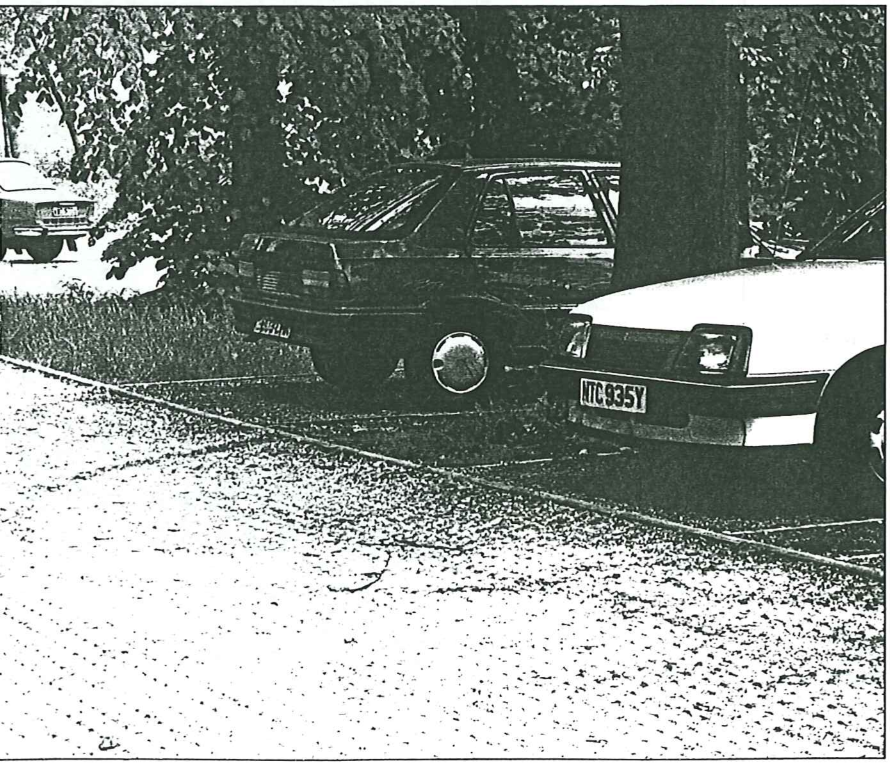
Easy to Lay

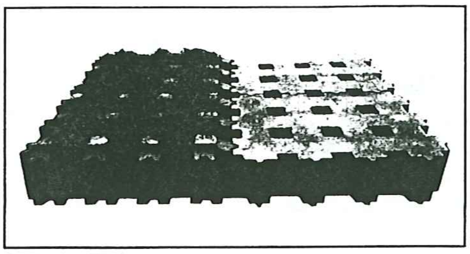
Either way, Grassgrid is economical and easy to lay – even on spillways and water-courses where familiar problems, like unstable sub-grade, are compounded by having to work in mud and at awkward heights and angles.

Thanks to the light weight and compact dimensions – 15.8 kg and 366 X 274 X 100 mm each unit – one man can do most jobs single-handed, without special equipment or training.

Grassgrid is dry-laid. Its interlocking design needs no further "fixing", except on steep slopes where shoring pins may be necessary.

Once laid, the only maintenance required is occasional mowing.





Unit Specification	
Dimensions (nominal):	366 X 274 mm 100 mm thick
Colour:	Natural Grey
Weight (nominal):	15.8 kg
Units per m²:	10
Surface Area:	15% concrete (85% inverted)
Base Area:	85% concrete (15% inverted)
Pack-size:	366 X 822 mm Plan 800 mm high (Two packs per non-returnable pallet)
- weight:	379 kg
- units :	24
- m²:	2.4
Concrete strength:	35N/mm²

Grass Standing and Hardstanding

The demand for hard landscaping is growing – but so too are environmental awareness and concern.

The bonus in specifying Grassgrid is that you can, without compromise, make green that would otherwise have to be grey.

One Product for all Applications

Grassgrid is used and recommended for hardstanding and verges, emergency access roads and roadside drainage covers, embankments and spillway channels, recreation areas, airfield taxiways and helipads, river and canal bed protection.

The product is designed for all applications. It requires only the addition of a 100–150mm sub-base along with bedding sand to rate it for the heaviest traffic.

Quality Control

Raw materials and product performance are monitored both before and after manufacture, to ensure that the products are of the highest quality. Our stringent in-house testing is carried out in accordance with the relevant British Standards.

Delivery and off-loading

ECC Building Products operate a fast efficient delivery service throughout Britain. Depending on location, delivery may be available on self-off-loading crane vehicles.

Technical Support

Technical support is available from ECC Building Products, who will advise on any specific application.

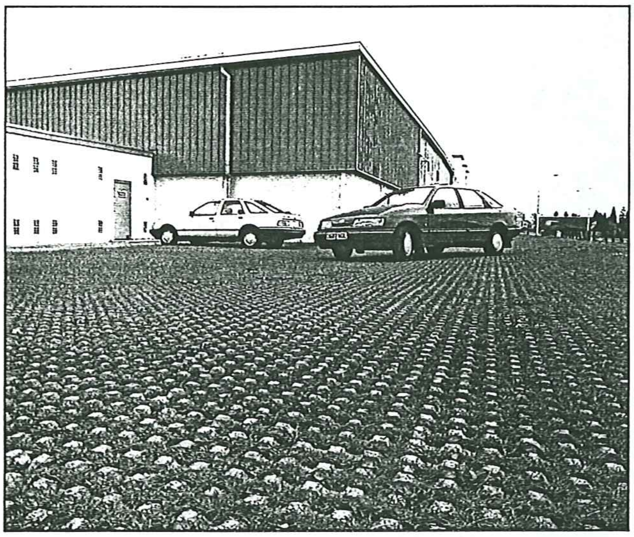
GRASSGRID FOR HARDSTANDING

Grassgrid can be specified, without necessarily strengthening the sub-grade, for all off-load areas where private cars or light commercial vehicles form the bulk of the traffic, and specifically: roadside verges and drainage channel covers, overspill carparks, recreational areas such as caravan sites and some emergency access roads.

One important effect of laying it is to stabilise the sub-soil and improve drainage – which, in turn, helps to defeat mud and preserve a uniform green "sward" year-round.

But it should be remembered, too, that chippings can be substituted for grass seed, or the units reverse-laid to present a smooth, self-draining surface ideal as a path or cycle-way.

Given a stable sub-grade, loads up to 5 tonnes deadweight can be parked indefinitely on Grassgrid without reinforcement.



INSTALLATION

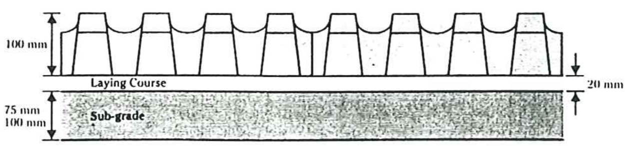
The following specification assumes pedestrian, private car and light commercial traffic only:–

No sub-base is necessary if the sub-grade is stable (see diagram). If it is not, incorporate a sub-base 75–100 mm thick, using DTP Type 1 material. Weed, compact and level before applying a laying course of 50% sharp sand and 50% loam, 20 mm thick.

Screed and roll lightly before laying the grassgrid units in rows – preferably with a restrained area. Tamp down with paviour's maul.

Finally, the cavities between the castellations should be filled to within 30 mm of the surface with good quality soil – then sown with grass seed and top-dressed with a further 20 mm of soil. Details of timing, recommended grass type and maintenance are on the back page.

The inherent strength of Grassgrid requires only the addition of a sub-base to specify it for heavy vehicle applications up to 11.5 tons.



The pyramid design of the cavities in which the grass is seeded provides such efficient weight distribution that it is regularly used "grass-side-up" for airport runway verges, taxiways and helipads, fire access and overspill lorry or container parks. Inverted to maximise its self-draining ability, Grassgrid is specified for farmyards and gated access.

Properly laid, on stable sub-grade, Grassgrid provides a uniquely effective solution to the dilemma of the landscape engineer, where the environment demands grass but the specification requires concrete.

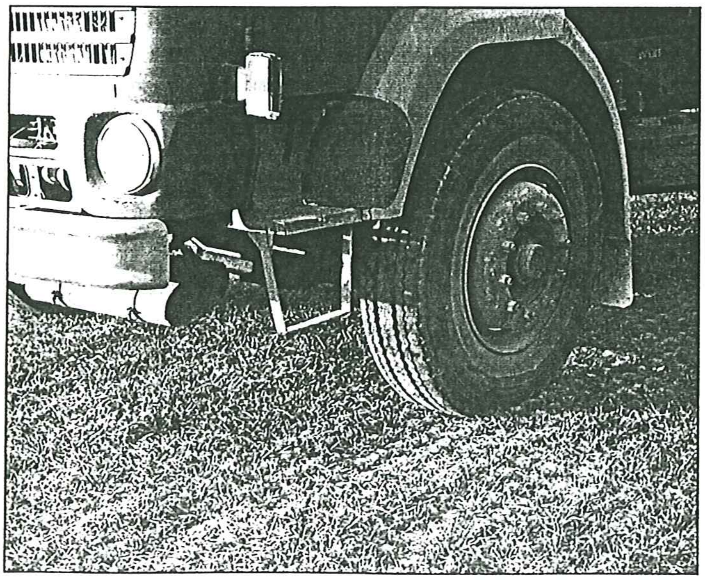
INSTALLATION

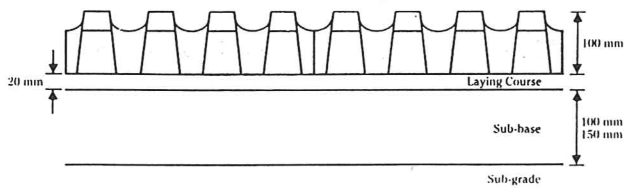
The following specification assumes heavy vehicle traffic, and includes fire access.

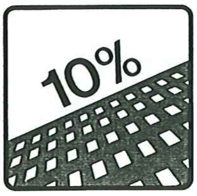
Ensure the sub-grade is stable and compact before laying a sub-base of DTP Type 1 material, 100–150 mm thick depending on the intensity of load anticipated.

Weed, compact and level the sub base before applying the laying course of 50% sharp sand and 50% loam, 20 mm thick. Screed and roll lightly before laying the Grassgrid units in rows – preferably within a restrained area. Tamp down with paviour's maul.

Finally, the cavities between the castellations should be filled to within 30 mm of the surface with good quality soil – then sown with grass seed and top-dressed with a further 20 mm of soil. Details of timing, recommended grass type and maintenance are on the back page.



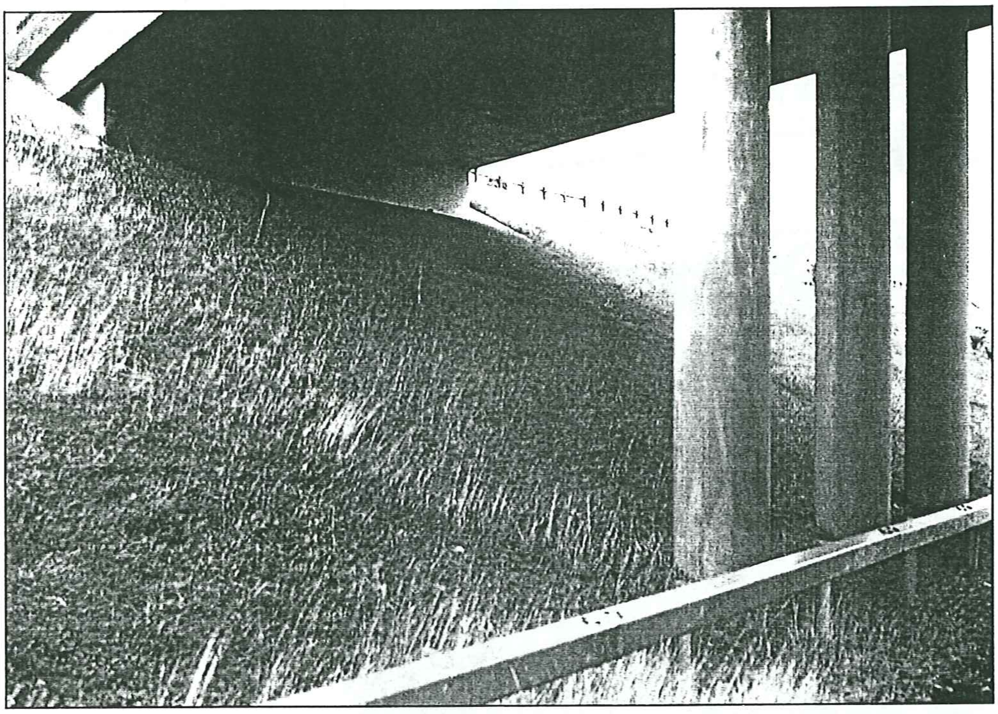




Grassgrid is the natural-looking alternative to conventional concrete solutions for cuttings, slopes and embankments. Applications also include flood-control – specifically, the creation of spillways and elements of dams and weirs.

In these, its load-bearing capacity is less important than its ability to stabilise the soil and prevent erosion. At the same time, it provides a "green alternative" to concrete, tar and steel.

Grassgrid is used and recommended for gradients up to 45 degrees. Where steeper slopes are encountered, or the sub-soil is unstable or rocky, our technical department should be consulted.



INSTALLATION

There are two methods of laying to slopes, neither of them requiring any special knowledge or equipment.

Before embarking on either, however, the sub-grade should be surveyed to make sure it is stable, compact and rock-free.

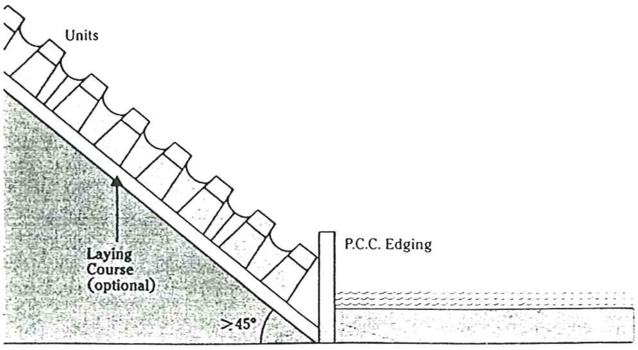
It found to be so, the laying course can be dispensed with, and the Grassgrid units laid directly on to the sub-grade.

In Method One, the units are laid from the bottom of the slope up, resting initially against embedded pre-cast concrete (PCC) edging. For steeper slopes, we recommend "staggering" the joints between units to increase structural integrity.

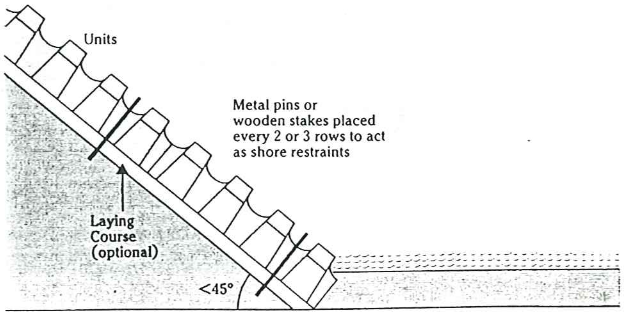
In Method Two, no special edging is necessary, and laying may commence from bottom or top. The crucial difference is that the vertical joints of the units must be staggered, and every second or third row staked with wood or metal pins to ensure stability.

Either way, after firmly tamping the units down, the cavities between the castellations should be filled to within 30 mm of the surface, with clean, friable soil, then sown with grass seed and top-dressed with a further 20 mm of soil. Details of timing, recommended grass type and maintenance are on the back page.

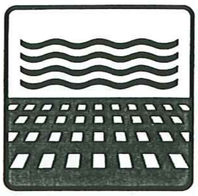
Method 1



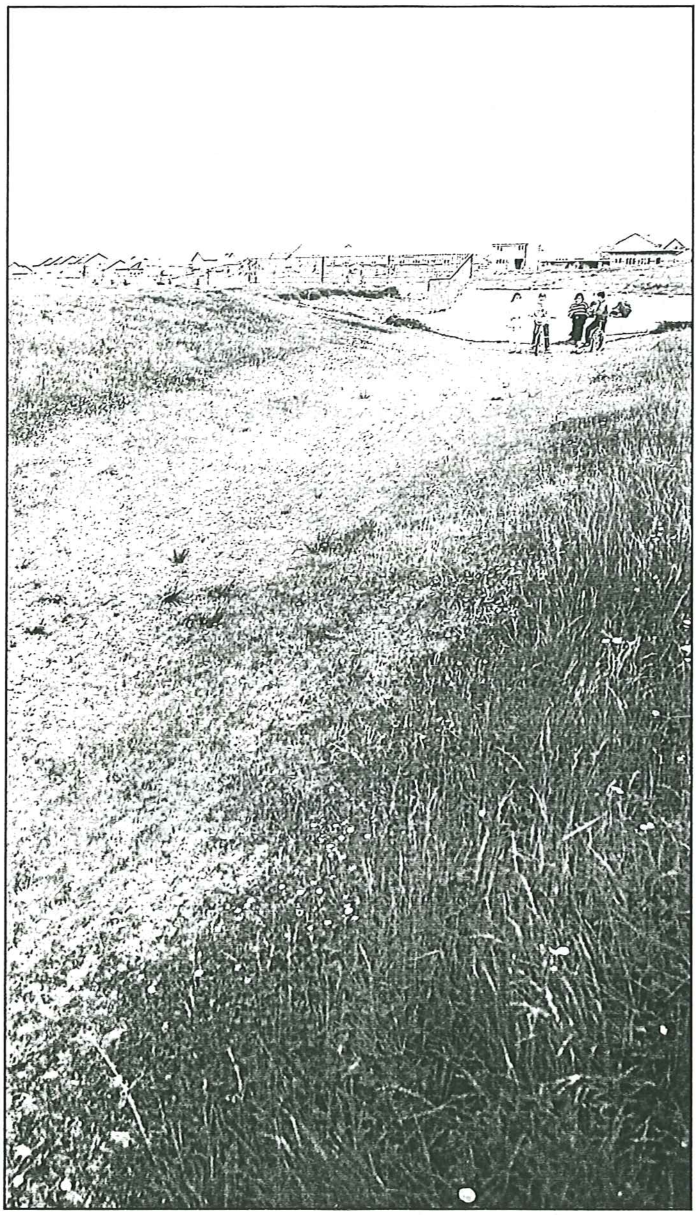
Method 2

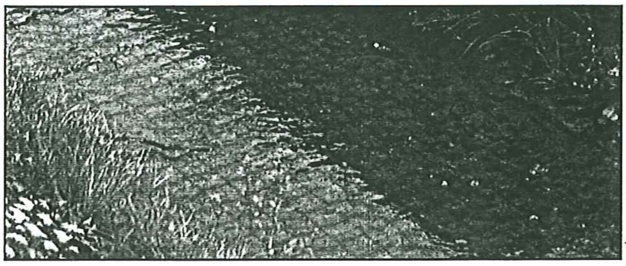


As well as above-water applications on banks, Grassgrid is effective below the surface, protecting the beds of rivers and water courses by stabilising the soil.



At the same time, aquatic grasses, reeds and plants can grow in and through the grid's honeycomb structure to provide effective and attractive camouflage while also encouraging natural wildlife.





INSTALLATION

To construct restraining banks, follow the installation procedure for Gradients, but take extra care to ensure that the sub-grade is stable. Method Two for installing units – incorporating wood or metal stakes as shoring pins – is preferred.

For the protection of river or canal beds, a different procedure should be followed – though, again, no special equipment or knowledge is necessary.

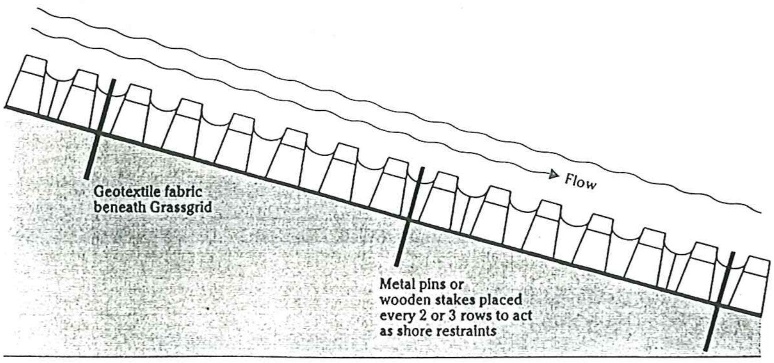
Assuming plants will be allowed to grow in or through the Grassgrid, but that its primary function is to stabilise the canal or river bed, a geotextile membrane, like Terram (R), must first be laid.

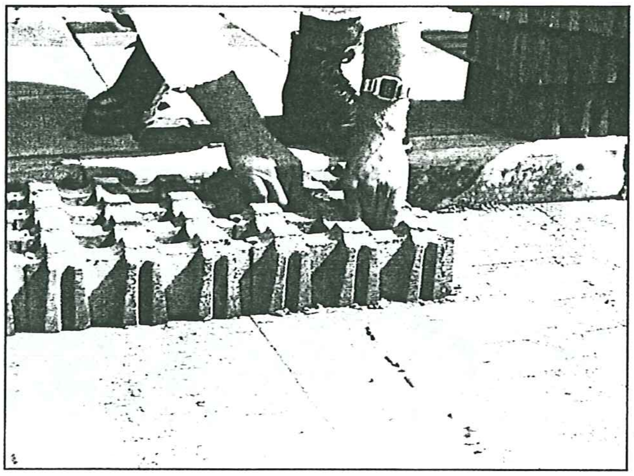
The membrane should be permeated with holes of between 0.2 mm and 0.4 mm (200–400 microns) to allow root penetration and provide some reinforcement of the stem as it grows.

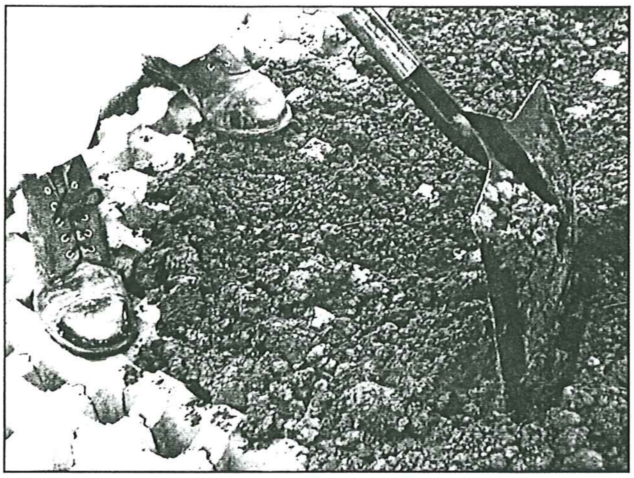
Weighed down by the units, the membrane will have the additional advantage of protecting the sub-soil and preventing erosion through flow intensity.

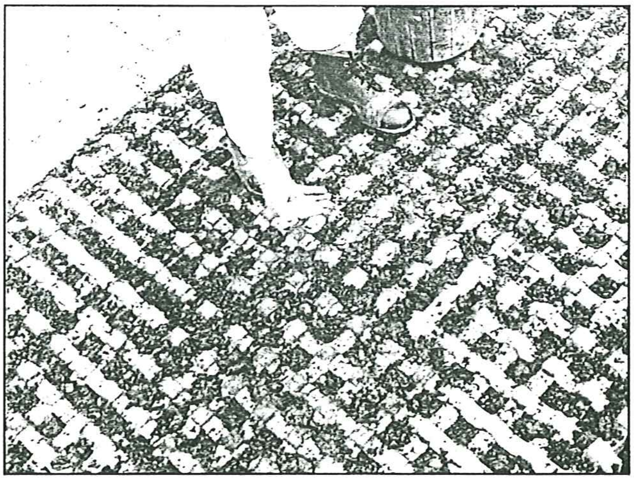
With the membrane in place, the Grassgrid units should be laid with the vertical joints staggered, and every second or third row staked, to increase stability.

Our technical department will advise on application, what grass or plant is best suited to the sub-soil of the bed to be protected. If a spillway, not normally or completely covered with water, follow the grassing instructions overleaf.









The grass type to emerge best from long-term tests commissioned from the Derbyshire College of Agriculture and Horticulture is British Seed Houses Mixture A7, comprising:-

* 50% Loretta: perennial rye grass
* 20% Baron: smooth-stalked meadow grass
* 20% Wintergreen: Chewings Fescue
* 10% Highland: "Brown Top"

The mixture should ideally be sown in Spring, and a minimum of four weeks allowed before the area is trafficked.

Simple maintenance

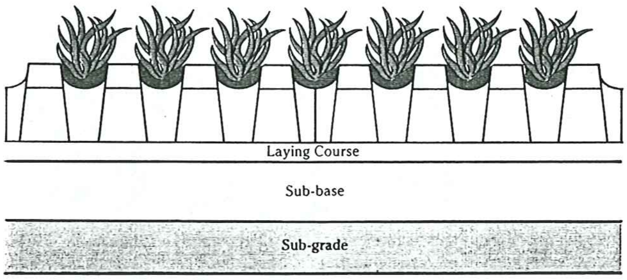
Where the traffic is heavy or constant, and the weather dry, water regularly to sustain growth and prevent the soil shrinking away from the concrete, causing water stress and, possibly, plant death.

Once the grass is established, it should be fertilised during April and May with a proprietary granular fertiliser.

Do not mow until the growth is strong and green – and then only to encourage further growth. Frequency will inevitably depend on the wear-and-tear factor.

If worn patches are apparent, they should be re-seeded in Autumn or Spring and, again, be allowed to establish for as long as possible.

For mowing Grassgrid, particularly on slopes, a "hover" is recommended.



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APPENDIX 2

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TITLE URBAN STORM DRAINAGE AND COMPENSATING TECHNIQUES. THE EXPERIENCE IN BORDEAUX (FRANCE)

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DATA WATER CONTENT, WATER POTENTIAL, HYDRAULIC CONDUCTIVITY

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.DATA BASEFLOW RECESSION, HYDROGRAPH RECESSION SLOPE, AREA-DISCHARGE CURVES, DESIGN STORM, COMPUTED HYDROGRAPHS, POROUS PAVEMENT STORAGE VOLUMES, POROUS PAVEMENT WATER QUALITY, SUSPENDED SOLIDS-DISCHARGE RELATIONSHIP, POLLUTANT YIELD, INFILTRATION LOSS

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DATA POLLUTION CONCENTRATION

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DATA POLLUTANT CONCENTRATION, DEPTH, UNIT SUPERSTRUCTURE TEMPERATURE

AUTHOR HOGLAND W, SPANGBERG A

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KEYWORDS UNIT SUPERSTRUCTURE, WATER QUALITY, INFLTRATION, DETENTION

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.AND THE UNITED STATES

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.DATA POLLUTION CONTENT

.AUTHOR HOGLAND W., WAHLMAN T.

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.KEYWORDS UNIT SUPERSTRUCTURE, POROUS PAVEMENT, INFILTRATION, STORMWATER
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.DATA RUNOFF, RAINFALL, RAINFALL INTENSITY, POLLUTANT CONCENTRATION,
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.AUTHOR ICHIKAWA A, HARADA S

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.KEYWORDS DRAINAGE, INFILTRATION, PEAK DISCHARGE, PERMEABLE PAVEMENT,
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.DATA RAINFALL INTENSITY, DRAINAGE RATE, LAG, ANTECEDENT WATER CONTENT,
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AUTHOR IZZARD C F

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KEYWORDS RAINFALL RUNOFF, OVERLAND FLOW HYDRAULICS, RUNOFF HYDROGRAPH, GUTTER FLOW HYDRAULICS, STORAGE

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AUTHOR JACKSON T J, RAGAN R M

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AUTHOR MEIN R G, LARSON C L

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KEYWORDS INFILTRATION MODEL, RAINFALL INTENSITY, INFILTRATION CAPACITY, WETTING FRONT SUCTION, SURFACE PONDING

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AUTHOR NIEMCZYNOWICZ J, HOGLAND W

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KEYWORDS POROUS ASPHALT, ADVANTAGES, DISADVANTAGES

DATA

AUTHOR SHINODA T

TITLE COMPARATIVE STUDY ON SURFACE RUNOFF BY STORMWATER INFILTRATION FACILITIES

PUBLICATION PROCEEDINGS OF THE FIFTH INTERNATIONAL CONFERENCE ON URBAN STORM DRAINAGE, SUITA, OSAKA, JAPAN, JULY, 1990

KEYWORDS RUNOFF CONTROL, STORMWATER INFILTRATION, WATER QUALITY, SURFACE CATEGORIES

DATA RUNOFF COEFFICIENTS, RUNOFF RATIOS, SURFACE CATEGORIES, SUSPENDED SOLIDS CONCENTRATIONS, RAINFALL, TIME, CLOGGED RUNOFF CAPACITIES.

AUTHOR SMITH D R

TITLE EVALUATIONS OF CONCRETE GRID PAVEMENTS IN THE UNITED STATES

PUBLICATION SECOND INTERNATIONAL CONFERENCE ON CONCRETE BLOCK PAVING, DELFT, APRIL, 1984

KEYWORDS CONCRETE GRID PAVEMENTS, STORM WATER RUNOFF, POLLUTION RUNOFF

DATA PAVEMENT TEMPERATURE, RAINFALL, RAINFALL VOLUME, RUNOFF VOLUME, RUNOFF COEFFICIENTS, PEAK RUNOFF FLOW

AUTHOR STENMARK C

TITLE LOCAL INFILTRATION OF URBAN STORM WATER IN COLD CLIMATE

PUBLICATION PROCEEDINGS OF THE FIFTH INTERNATIONAL CONFERENCE ON URBAN STORM DRAINAGE, SUITA, OSAKA, JAPAN, JULY, 1990

KEYWORDS COLD CLIMATE, INFILTRATION CAPACITY, PERCOLATION BASIN, PERMEABLE ASPHALT, SNOW MELT

DATA INFILTRATION RATE

.AUTHOR TAMAI N, TANAKA Y, JEEVARAJ C G

.TITLE UNSATURATED SEEPAGE FLOW THROUGH PERVIOUS PAVEMENT

.PUBLICATION PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON URBAN STORM DRAINAGE, LAUSANNE, 1987

.KEYWORDS PERVIOUS PAVEMENT, MATHEMATICAL MODEL, GROUNDWATER RUNOFF, HYDRO-GEOLOGICAL COEFFICIENTS

.DATA GROUNDWATER LEVEL, TIME, RAINFALL INTENSITY, OUTFLOW HYDROGRAPH

.AUTHOR TAYLOR D W

.TITLE FUNDAMENTALS OF SOIL MECHANICS

.PUBLICATION PUBLISHED BY JOHN WILEY AND SONS, NEW YORK, LONDON, 1948

.KEYWORDS PERMEABILITY (CHAPTER 6)

.DATA

.AUTHOR THELEN E, GROVER W C, HOIBERG A J, HAIGH T I

.TITLE INVESTIGATION OF POROUS PAVEMENTS FOR URBAN RUNOFF CONTROL

.PUBLICATION THE FRANKLIN INSTITUTE RESEARCH LABORATORIES, PHILADELPHIA, PENNSYLVANIA, USA, MARCH 1972

.KEYWORDS POROUS PAVEMENT, HYDROLOGY, DRAINAGE, POLLUTION, BACTERIA, PAVEMENT COSTS

.DATA SUBGRADE SOIL PERMEABILITY, PAVEMENT AGGREGATE GRADATIONS, FREEZE THAW STABILITY, ASPHALT PENETRATION VALUES, MAXIMUM DAILY RAINFALL, MAXIMUM DAILY PRECIPITATION ZONES, BACTERIAL ACTIVITY, PAVEMENT COSTS, PAVEMENT SERVICE LIFE

AUTHOR URBAN J.B., GBUREK W.J.

TITLE STORM WATER DETENTION AND GROUNDWATER RECHARGE USING POROUS ASPHALT - EXPERIMENTAL SITE

PUBLICATION INTERNATIONAL SYMPOSIUM ON URBAN STORM RUNOFF, UNIVERSITY OF LEXINGTON, KENTUCKY, JULY 1980.

KEYWORDS STORM WATER DETENTION, GROUNDWATER RECHARGE, POROUS PAVEMENT

DATA AGGREGATE COMPOSITION, HYDROLOGICAL DATA

AUTHOR van de VEN H M, ZUIDEMA F C

TITLE PROGRESS SINCE 1979 IN THE NETHERLANDS

PUBLICATION PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON URBAN HYDROLOGY, BALTIMORE, MARYLAND, USA, JUNE, 1983

KEYWORDS URBAN HYDROLOGICAL MODELLING, URBAN RUNOFF, WATER QUALITY, INFILTRATION, PERVIOUS PAVEMENTS, SEWER SYSTEMS

DATA RAINFALL INTENSITY, INFILTRATION RATE, GROUNDWATER LEVEL

AUTHOR VAUCLIN M, KHANJI D, VACHAUD G

TITLE EXPERIMENTAL AND NUMERICAL STUDY OF A TRANSIENT, TWO DIMENSIONAL UNSATURATED-SATURATED WATER TABLE RECHARGE PROBLEM

PUBLICATION WATER RESOURCES RESEARCH, VOL. 15, NO. 5, OCTOBER 1979

KEYWORDS MATHEMATICAL MODEL, SHALLOW WATER TABLE, INFILTRATION, UNSATURATED FLOW, SATURATED FLOW, RECHARGE

DATA WATER PRESSURE, WATER CONTENT, HYDRAULIC CONDUCTIVITY, WETTING FRONT, DEPTH, DEPTH, WATER VOLUME, TIME, WATER TABLE DEPTH, TIME OF TRANSFER, FLUX, VOLUME OUTFLOW

AUTHOR WADA Y, SIRONO O, MORIE T

TITLE CONTROLLING URBAN STORM RUNOFF WITH PERMEABLE DRAIN

PUBLICATION PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON URBAN STORM DRAINAGE, LAUSANNE, 1987

KEYWORDS STORM WATER CONTROL, PERMEABLE DRAIN, PERMEABILITY

DATA RAINFALL INTENSITY, DISCHARGE, PERMEABILITY, HYDROGRAPHS

AUTHOR WADA Y, MIURA H

TITLE EFFECT AND EVALUATION OF STORM WATER CONTROL BY PERMEABLE COMBINED INFILTRATION FACILITIES FOR CONTROLLING STORM RUNOFF

PUBLICATION PROCEEDINGS OF THE FIFTH ANNUAL CONFERENCE ON URBAN STORM DRAINAGE, SUITA, OSAKA, JULY, 1990

KEYWORDS PERMEABLE PAVEMENT, INFILTRATION CAPACITY, INFILTRATION MECHANISM, COMPUTATIONAL MODEL

DATA RAINFALL INTENSITY, DISCHARGE, TIME, INFILTRATION LOSS

AUTHOR WALKER R M

TITLE GRASSCRETE. STORM WATER MANAGEMENT - THE CASE FOR CONCRETE POROUS SURFACING

PUBLICATION GRASS CONCRETE LIMITED, WAKEFIELD, MARCH 1984

KEYWORDS STORM WATER MANAGEMENT, URBAN DEVELOPMENT, POROUS PAVEMENTS, RETENTION STRUCTURES, GRASSCRETE

DATA