VOIDS AND COVER TO STEEL IN PRECAST CONCRETE PIPES:

REPORT OF WORKING GROUP

Concrete Pipe Association
of Australasia

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1. INTRODUCTION

This report has been prepared in response to a request from the Director, Standards Association of New Zealand. The authors were asked to examine the significance of voids and cover to steel in respect of the durability of precast concrete pipes, with special attention to the relevance, if any, of the manufacturing method. The request was initiated by a conflict of opinion within the Concrete Pipes Project Committee as to whether the revision of NZS 2238:1968, "Specification for Precast Concrete Drainage and Pressure Pipes," should incorporate requirements for depth of concrete cover over steel differentiating between the products of different manufacturing processes.

NZS 2238, when first written, applied only to pipes manufactured by the process of centrifugal casting (spinning), for the simple reason that these were the only pipes then manufactured in this country. It has been stated that NZS 2238 has proved generally satisfactory for spun pipes and, with certain reservations, we would agree with this opinion. However, pipes manufactured by another method (Hydrotile pipes) have recently appeared on the New Zealand scene. Simultaneously, an argument has developed as to whether the provisions of NZS 2238 are adequate for this new type of pipe. Before becoming involved in the detail of this argument, however, it is essential to examine the nature of NZS 2238.

2. NATURE OF PIPE SPECIFICATION

One or other of two alternatives is generally employed in the preparation of a specification for any manufactured product. These alternatives are as follows:

1. Produce such descriptions of the materials to be used and the manufacturing methods to be employed as will guarantee a satisfactory end-product.
2. Produce a set of requirements for test performance of the end-product such that the competence of the product for its intended function will be demonstrated.

NZS 2238 is basically a specification of the second type. It mainly contains requirements for the test performance of pipes although it also, perhaps unnecessarily, makes some reference to the materials to be used in manufacture. The specification contains requirements for workmanship, finish and uniformity of dimensions which are designed to ensure ease of assembly of pipes into a line, a load test requirement intended to ensure the ability of the pipes to withstand the stresses to which they may be subjected in laying and in service and a hydrostatic pressure test requirement designed to assess the efficiency of the pipes as conduits for liquid. The fourth obvious factor of importance, viz. some guarantee of satisfactory durability, is given recognition via two requirements, one for minimum cover over reinforcement and the other for water absorption of the concrete.

Bearing in mind that the relationship between durability on the one hand and the requirements for steel cover and water absorption on the other is not capable of quantitative definition, it may nevertheless be stated that NZS 2238 is a performance type specification. Moreover, it is apparent from a study of the opinions expressed by members of the Concrete Pipes Project Committee, which began revision of NZS 2238 in April, 1971, that this essential nature of the specification is to be retained. However, the question which cannot be settled and around which the divergence of opinion revolves, is whether the same set of requirements will give a similar guarantee of durability for both spun and Hydrotile pipes.

It is now generally accepted that both methods of manufacture can produce concrete of acceptable porosity in terms of the requirements of NZS 2238. The point at issue, however, is whether the requirement for concrete cover over reinforcing steel should apply to both. In the proposed amendment to Clause 15 of NZS 2238, prepared by the Project Committee, it has been suggested that the minimum cover prescribed in Table 5 of NZS 2238 (as low as ¼") should apply only to spun pipes, and that for other casting methods the cover should not be less than 0.60 inch. Before attemtping to evaluate this proposal, it is essential to describe the differences between spun and Hydrotile pipes which formed the basis for the viewpoint that they should be treated differently in terms of the requirements for cover over steel.

3. DIFFERENCES BETWEEN SPUN AND HYDROTILE PIPES

In the traditional centrifugal casting (spinning) process, a semi-fluid concrete is fed into a steel mould mounted on spinning rollers with its axis horizontal. The reinforcing cage is positioned in the mould before filling commences. As soon as the mould is filled and the concrete uniformly distributed within it, the speed of the rollers is increased. High centrifugal forces are thus imparted to the concrete (sometimes with associated vibration), and the denser aggregates and cement move outward towards the mould face displacing [illegible] plus water inward as consolidation proceeds. The water which accumulates along the barrel of the pipe is trowelled out before the interior surface is finished, and spinning then ceases. The pipe is usually steamed overnight and stripped from the mould the following morning.

The spinning process generally achieves a uniformly high density and low ultimate W/C ratio throughout the pipe. Contact between concrete and steel reinforcing is generally intimate.

Certain features are essential in concrete used in the spinning process. It must have a fairly high cement content for strength and permeability reasons. Its workability must be such that it will spread readily and will completely encase the reinforcing cage. It must have sufficient cohesiveness to prevent gross segregation during mould filling, but not so high as to prevent or inhibit the inward displacement of surplus water during the high-speed spinning phase.

In the Hydrotile process the reinforcing cage is positioned within a static vertical steel mould and a semi-dry concrete is trowelled onto the interior face, encasing and covering the steel. The forming operation consists of pouring concrete into the top of the mould whereupon it is distributed and packed tightly by a rotating system of fins and rollers driven upward by a vertical shaft. The pipe is stripped immediately. Speed of production and immediate reuse of moulds are features of the method.

The Hydrotile process also uses concrete of high cement content and low W/C ratio, and is capable of producing pipes with high strength and density. However, certain difficulties were encountered in the initial application of the system in this country.

The consistency (wetness) of concrete used in Hydrotile pipe manufacture must be low. Overwet concrete causes problems of mould adhesion and deformation of the pipe on stripping. When the concrete is sufficiently dry to preclude these problems, the rotating compactor exerts extremely high pressures in moulding it around the reinforcing. In early production it was found that the application of these high rotating forces resulted in considerable wind-up in the reinforcing cage. The torque thus stored inthe steel was resisted by mould friction and the stiffness of the surrounding concrete until the pipe was stripped. At this stage some restoration of the twist occurred with consequent deformation of the pipe.

In pipes containing twisted reinforcing cages it was found that cavities up to about 0.015" in thickness existed along the steel-concrete interfaces. In some cases these cavities were of such size and extent as to effectively eliminate the contact between concrete and steel. Understandably this state of affairs led to severe criticism of the Hydrotile process, and intensive remedial measures were begun. Experience in other countries was of little help at this point as the process had not been applied elsewhere in the manufacture of reinforced pipes of the length and wall thicknesses common in New Zealand.

The programme of modification of the Hydrotile machines and their operational procedures has been closely watched by Ministry of Works officers. It is now fair to say that the modifications have resulted in effective elimination of cage twist with a significant reduction in both size and extent of cavities. Other procedural alterations have provided a uniformity of compaction which was not characteristic of pipes from early production. However, probably as the combined effect of cage vibration or distention during moulding and the low workability of the concrete used in the Hydrotile process, some cavity formation still persists. The question of its significance is accordingly still pertinent.

It was this question of the significance of cavity formation which could not be resolved by the Concrete Pipes Project Committee. A majority of the membership supported the opinion that some degree of risk of poor durability would be associated with the presence of voids adjacent to the steel. Their viewpoint could be summarised as follows:

1. Pipes manufactured by the Hydrotile process could be more susceptible to steel corrosion than are the traditional spun concrete pipes.
2. Hydrotile pipes could accordingly be inferior in durability.
3. The revision of NZS 2238 should incorporate a safeguard against this potential inferiority by prescribing extra cover to steel in Hydrotile pipes.

The above attitude was crystallised in the proposed amendment to Clause 15 of NZS 2238, but agreement could not be reached on its acceptability. The major problems facing the Project Committee were that little definitive technical information of direct relevance to the matter was available to it, and much of the discussion was biased by the obvious commercial implications of the final decision. At this point the Director of SANZ called for the assistance of this Working Group in a study of the question of whether, because of the presence of voids or cavities adjacent to the steel, Hydrotile pipes are likely to suffer steel corrosion more rapidly than spun pipes, and if so, whether the difference will be significant in terms of durability.

Our observations and deductions are presented below, but are preceded by a discussion, in the next section of this report, of the current state of knowledge of the mechanism of steel corrosion in concrete. This section contains some technical complexities, but is included in this report to assist the Project Committee in evaluating the conclusions which we finally present.

4. MECHANISM OF STEEL CORROSION IN CONCRETE

Before considering the special case of steel corrosion in concrete, it will be useful to consider the general nature of rust and the factors affecting its formation.

Point 1

Steel rusts only in the presence of water and oxygen. In the complete absence of either, rusting cannot occur.

Point 2

There is no stoichiometric formula for rust but it can be identified as $Fe_2O_3.nH_2O$ in which the value of n depends on the conditions of formation and can vary greatly in a single sample of rust from one spot to another. This may account for the variation in colour on rusty steel surfaces.

Point 3

Since the exact chemical nature of rust is not known, it is not surprising that the exact mechanism involved in the rusting process is not known either. In fact the process may vary somewhat from one environment to another. It is fairly certain, however, that both oxidation of iron (formation of Fe^{++} ions with loss of electrons) and an electron-demanding reduction reaction between oxygen and water (to form hydroxide ions OH^-) are primary steps in the process. These reactions may be written as follows:

Oxidation: $Fe_{(c)} = Fe^{++}{}_{(aq)} + 2\ e^-$

Reduction: $O_{2(g)} + 2H_2O_{(1)} + 4\ e^- = 4OH^-{}_{(aq)}$

Where the subscripts refer to the phase of the substance. Thus c = crystalline, aq = aqueous solution, g = gas and 1 = liquid.

Point 4

The oxidation and reduction reactions occur at points on the surface of the steel which differ in electric potential. This difference in potential may be the naturally-occurring difference between the grains of iron and the impurities which it contains, or it may be an externally-impressed potential difference. In either case the points of potential difference form the poles of an electrolytic cell. The point of higher potential at which oxidation of iron occurs is the anode. The point of lower potential at which the reduction reaction occurs is the cathode.

In the functioning of an electrolytic cell such as this, the free electrons produced at the anode flow through the steel to the cathode where they become available for the reduction reaction. However, for continuing operation of the cell, the circuit must be completed by an uninterrupted water path between cathode and anode.

Point 5

The oxidation of iron at the anode is the beginning of corrosion. The Fe^{++} ions produced at the anode are attracted towards the negatively-charged cathode and accordingly drift outward from their point of production. The OH^- ions produced at the cathode and those occurring naturally in the water are attracted towards the positively-charged anode. The subsequent chemical reactions are not well understood. However, in one possible continuation of the corrosion process the ions of iron, Fe^{++}, react with the incoming hydroxide ions, OH^-, to form ferrous hydroxide which is precipitated as a solid.

$$Fe^{++}_{(aq)} + 2\ OH^-_{(aq)} = Fe\ (OH)_{2(s)}$$

With further oxidation (requiring a supply of oxygen) this hydroxide is changed to the ferric form as follows:

$$Fe\ (OH)_{2(s)} + \tfrac{1}{4}\ O_{2(g)} + \tfrac{1}{2}\ H_2O_{(1)} = Fe\ (OH)_{3(s)},$$

and the rust formation is given by

$$2\ Fe(OH)_{3(s)} + (n-3)\ H_2O_{(1)} = Fe_2O_3.nH_2O_{(s)}$$

Point 6

Electrolytic corrosion is accelerated when the water contains an electrolyte. The presence of the electrolyte allows greater ionic current to flow in the solution and hence speeds the corrosion. It also allows the reactions involving oxidation of iron and reduction of oxygen to occur at widely-separated points, thus encouraging the formation of large-scale corrosion cells.

Point 7

Certain environmental factors tend to prevent the start or inhibit the continuation of galvanic corrosion of steel. The most effective of these is a high level of alkalinity in the surrounding environment. Iron is strongly resistant to corrosion in highly basic solutions as OH^- ions coat the surface and prevent oxidation.

Another important inhibiting mechanism is polarisation of the corrosion cell. During the flow of current in the cell, OH^- ions are drawn towards the anode. Simultaneously H^+ ions move towards the cathode where a film of hydrogen gradually forms. If this film is not removed, the cell ceases to function and further reaction at the anode is prevented. The cell is now polarised. If, however, the accumulated hydrogen is evolved as a gas and escapes from the cathode, or if it is removed by reaction with some other element, the cell is depolarised and reaction can proceed. Oxygen dissolved in the water will readily produce depolarisation as it combines with hydrogen to form water.

However, even in the event that the galvanic cell is constantly depolarised by a plentiful supply of oxygen at the cathode, another inhibiting mechanism may operate. This relies on an equally plentiful supply of OH^- ions and oxygen at the anode. In such circumstances the rusting occurs in close contact with the steel surface. The film so formed is adherent and protective, and may significantly inhibit further corrosion. This is the typical condition when steel rusts in moist air.

Considering now the special case of steel corrosion in concrete, the following factors may be considered significant.

1. For rusting to occur, both water and oxygen must have access to the surface of the steel. If the corrosion is to be sustained, the water must be present in sufficient quantity to provide an ionic current path between cathode and anode, and sufficient oxygen must be available at the cathode to prevent polarisation of the cell. In the absence of water (as in dry concrete) or in the absence of a plentiful supply of dissolved oxygen (as will be the case in concrete of low permeability) the galvanic cell will not be depolarised and its corrosion potential will be negligible.

   Concrete pipes are generally well supplied with water. When embedded in the ground they will usually be saturated or nearly so. While held in stockpiles they are frequently wetted by rain. In the former case the oxygen availability would probably be substantially restricted, but pipes above ground are well supplied with oxygen. The availability of the oxygen at the steel-concrete interface will of course be determined by the permeability and thickness of the concrete cover. Low concrete permeability and high cover thickness will obviously be beneficial, but critical values for either are not easy to predict. Limited access of oxygen to the anode in a corrosion cell may result in the rust forming at some distance from the metal surface. In such circumstances rust produced from steel embedded in the concrete will not provide a protective film on the steel surface, and the pressure of accumulating rust between the steel and the surface of the concrete may lead to cracking along the line of the steel.

   Thus, although it is not possible to provide definitive evidence as to which combinations of cover thickness and concrete permeability will provide absolute security from rusting of embedded steel, it is reasonable to postulate that from the point of view of oxygen availability pipes exposed above ground will be significantly more susceptible to steel corrosion than those buried in the ground.

2. Portland cement concrete is highly alkaline with a pH normally higher than 12, and while this alkaline condition persists, steel encased in the concrete is well protected from corrosion. However, any reduction of alkalinity at the steel-concrete interface may create a potentially-deleterious situation. Such reduction is most likely to be caused by carbonation which is the reaction of atmospheric carbon dioxide with calcium hydroxide (or other cement hydrate materials) in the concrete to form calcium carbonate. However, carbonation

does not penetrate deeply into well-compacted concrete, and provided the clear concrete cover over the reinforcement exceeds the carbonation depth, carbonation induced corrosion is not likely to occur.

Concrete exposed to air is more likely to undergo carbonation than is concrete buried underground, firstly because of the greater availability of carbon dioxide in air, and secondly because concrete is carbonated most readily at moderate humidity levels. In considering potential causes for the onset of steel corrosion in concrete pipes, it is accordingly reasonable to expect that carbonation will be a significant factor only in pipes exposed to the air.

3. Cracks or porous areas in concrete pipe surfaces may be expected to provide ready-made paths for the ingress of carbon dioxide and oxygen to the steel, with consequent alkalinity reduction and subsequent rusting. It would seem equally probable that cavities extending along the surfaces of the steel would act as extensions of the cracks or porous zones and so induce the corrosion to progress along the steel from the point of initiation. Furthermore, it might be expected that this mechanism would be more probable during long-term air storage than after burial in the ground. Both carbon dioxide and oxygen would be more available during air exposure, fluctuating levels of humidity and temperature would cause variations in crack width and hence assist the penetration of the aggressive materials, and high air temperatures would significantly accelerate the rate of corrosion once it had begun.

5. EXAMINATION OF CONCRETE PIPES

In view of the considerations outlined immediately above it was decided to restrict the examination of spun and Hydrotile pipes to those available from stockpiles, and a considerable number of pipes, pipe sections and cores were inspected closely. All the pipes examined initially were supplied from Ministry of Works stocks, but a large number of Hydrotile pipes rejected for various reasons during the initial stages of plant commissioning were subsequently examined at a dumping ground at Silverstream. This latter course was adopted as a means of inspecting Hydrotile pipes of maximum possible age.

The spun pipes examined were all 9" or 12" in diameter. The Hydrotile pipe diameters were mostly 12" but ranged up to 18". Ages of the spun pipes ranged from 4 months to 5 years and those of the Hydrotile pipes from 3 months to 3-5 years. All the pipes were progressively broken throughout their length and inspected carefully for such features as cover over reinforcement, presence of cavities adjacent to the steel, reinforcing cage twist, cracking, porous areas, steel-concrete bond and incidence of rusting. Our findings were as follows:

(a) Cover over reinforcement

Both types of pipe showed considerable variation in the thickness of concrete cover over the steel. In the spun pipes, in spite of the presence of reinforcement locating pins, covers as low as 1/32" were discovered. This condition was generally associated with distortion or improper centring of the wire cage, but was in some cases the result of variation in wall thickness due to distortion at the mould joint. In the Hydrotile pipes cover generally exceeded 3/16", but at spigot ends and in the collar sections thicknesses as low as ⅛" were discovered.

In terms of uniformity of cover the Hydrotile pipes were generally superior to the spun pipes, the difference being particularly apparent in the more recent production of Hydrotile pipes with cage twist effectively eliminated.

(b) Cavities adjacent to steel

The presence of cavities was found to be a common characteristic of early production Hydrotile pipes. Cavities generally occurred along both longitudinal and circumferential rods and were up to 0.015" in depth. They were usually located on the outer faces of the steel and appeared to be associated with cage twist during production. In many cases the presence of cavities had effectively destroyed the bond between concrete and steel.

Modifications to the Hydrotile machine have now overcome the problem of cage twist and our examination of recent pipe production has disclosed a marked reduction in both size and extent of cavities.

(c) Reinforcing cage twist

This feature was discerned only in the Hydrotile pipes. In some pipes the reinforcing cage was twisted by about 70° in the 8' length. The consequent shortening of the cage left as much as 2" of the spigot unreinforced. However, as mentioned above, this problem has now been eliminated.

Although cage twist was not encountered in any of the spun pipes, another deficiency was discovered in them. This was the presence of a completely unreinforced gap of about 5" between the barrel steel and the collar reinforcing in 9" diameter spun pipes manufactured in 1972.

(d) Cracking and porous areas.

Both types of pipe received from stockpiles were generally free of visible cracking, but some of the discarded early-production Hydrotile pipes contained numerous shear cracks up to 0.01" wide obviously due to the torque associated with restoration of cage twist on stripping.

Some porous poorly-consolidated zones were apparent in Hydrotile pipes, generally in the collar and spigot regions, and a few minor harsh improperly-compacted zones were discerned in spun pipe where the larger stones had formed pockets against the steel. It is of interest to note here that some of the 9" diameter spun pipe with wall thicknesses of the order of 1" contained aggregate as large as $\frac{3}{4}$"

(e) Steel concrete bond

Because of the presence of extensive cavities, bond between concrete and steel in the early Hydrotile pipes was virtually non-existent. However, intimacy of contact between the reinforcement and the surrounding concrete was found to be much improved in pipes of more recent production. In all the spun pipes examined the concrete was well moulded around the steel. In both types of pipe, however, the bright polished condition of much of the wire used in forming the reinforcing cages had precluded the development of high bond strength between concrete and steel. Spun pipes 5 years old contained steel which was still shiny and could be detached easily from the surrounding concrete.

(f) Incidence of rusting

Major attention was given to this factor in the examination of the pipes, and whenever an area of rusting was detected careful efforts were made to discover the contributing causes. Some degree of rusting was discovered in most of the pipes examined and it was found that recently produced rust could readily be differentiated from rust existing on the steel before its encasement in concrete.

Several instances of rusting were detected in spun pipes only 4 months old. In each case the steel was located only 1/32" below and parallel to the concrete surface and rusting was progressing along the outer face of the steel. In one case the steel direction could be traced for some distance by rust staining on the concrete surface, and fracture of the concrete surface by spalling appeared to be imminent. In all cases the concrete appeared to be adequately compacted and the rusting could only be attributed to inadequate cover.

Similar examples of minor recent rusting were discerned in a spun pipe 5 years old. The concrete in this pipe was extremely dense and hard but the thickness of cover over the rusting steel was only about 1/16". It is probable that carbonation had taken 5 years to penetrate to the 1/16" depth and rusting had begun as a result of the reduction in alkalinity. The basic deficiency was of course inadequate cover. The same pipe showed no sign of recent rust where the cover was of the order of only 3/32". Cage locating studs in the same pipe had rusted inward about 1/16" at which depth the corrosion had apparently been choked off. An old longitudinal crack about 0.005" wide at the concrete surface had allowed rusting to occur at each steel-crack intercept but the rusting had not progressed along the steel.

The examination of Hydrotile pipes from stockpiles disclosed a greater incidence of rusting in the older pipes than in those produced more recently. This difference did not appear to be solely attributable to age differential but was more obviously a reflection of the improved quality of later production. In the older pipes zones of rusting were discovered in poorly consolidated areas in the collar and spigot sections. This rusting was apparently not due to inadequacy of the cover which in all cases exceeded ¼". Nor could it be blamed on the presence of cavities around the steel as these simply constituted extensions of the open texture of the surrounding concrete. The rusting was quite obviously due to high permeability resulting from inadequate compaction of the concrete.

The only instance in which the presence of a cavity adjacent to the steel had evidently contributed to the spread of corrosion in Ministry of Works stockpiled Hydrotile pipes was discovered in a pipe about 2 years old. In this pipe, a welded junction between longitudinal and circumferential rods had been distorted and was lying about 3/16" from the concrete surface. Rusting had commenced at this point and spread about 4"along the circumferential rod, but only on the face of the steel exposed to the cavity.

No rusting was discovered in stockpiled Hydrotile pipes less than 6 months old although the presence of cavities around the steel was a common characteristic. The absence of rusting was apprently associated with a greater uniformity in both density and cover to the steel than that displayed by older pipes.

Our examination of discarded Hydrotile pipes at the Silverstream dump also provided some useful information on rusting. The pipes were, of course, rejects, and hence were not representative of the quality of marketed Hydrotile pipes. It was found that rusting was always associated with a zone of poor compaction, or a wide crack (0.010" or more), or very low cover (usually less than 3/16"), or a combination of these. The examination also provided ample evidence that rusting so initiated can progress along cavities surrounding the steel.

The most significant feature of the corrosion in these discarded pipes, however, was the fact that it had progressed to a markedly greater degree in pipe sections exposed to the air than in those partially or wholly buried in the ground. In fact some buried sections of very poorly compacted concrete had shown no significant deterioration in a period of over 3 years.

(g) Tests on cored specimens

Cored sections of pipe wall from both spun and Hydrotile pipes were taken for examination of cover thickness and width of cavities around the steel. These cores were also used for measurements of water absorption and depth of surface carbonation.

The carbonation depth was determined by treating the core surfaces with phenolphthalein. In this technique carbonated regions remain uncoloured while zones containing free calcium hydroxide show a pink colouration. In no case was carbonation found to extend more than 1/16" into well-compacted concrete even at ages of 3 years, and in this respect there was no noticeable difference between spun and Hydrotile pipes.

A large number of water absorption tests were made on cores. These showed that spun pipes of all ages complied comfortably with the NZS 2238 maximum limit for pressure pipes of 6.5 per cent of dry weight. Early - production Hydrotile pipes showed significantly higher absorption values, generally in the range 6.0 to 8.5 per cent. More recently - produced Hydrotile pipes have shown much lower water absorption values rarely exceeding 6.0 per cent. This supports our earlier contention that modifications to the Hydrotile pipe production process have resulted in a higher quality product.

6. CONCLUSIONS FROM TESTS AND EXAMINATIONS

Our tests and examinations of concrete pipes have led us to the following conclusions.

1. All instances of steel corrosion in concrete pipes can be attributed to inadequate steel cover, high concrete permeability or the presence of cracks. Various combinations of cover thickness, concrete density (and crack width) may provide the same level of protection or risk in a given environment, and it is accordingly difficult to assign confident safety limits to any one of these three parameters. In certain circumstances, cover as thin as 1/16" may apparently provide good long-term protection against steel corrosion, but only if the concrete is (free of cracks and) very dense.

2. Cavities adjacent to the steel reinforcement are not responsible for initiation of rusting but may encourage its subsequent progress along the steel.

3. In spite of the difficulty of specifying safe crack width or essential concrete density, it is our view that there is a negligible likelihood of steel corrosion in concrete pipes with or without cavities around the steel, provided the cover always exceeds ¼" and the concrete is densely compacted.

4. Steel corrosion is more likely to occur in pipes exposed to the air and subject to wetting and drying than in those buried in the ground. It is probable, in fact, that pipes in the ground suffer little risk of steel corrosion. Aggressive groundwaters or effluents carried by the pipes are more likely to attack the concrete itself.

5. In the light of the conclusions above, there appears to be no justification for differentiating in the proposed revision of NZS 2238 between the cover requirements for spun and Hydrotile pipes. A more fruitful provision would be to insist that specified minimum cover thicknesses are always complied with. A probe type 'covermeter' currently being developed at Ministry of Works Central Laboratory will hopefully provide

a means of determining the depth of embedment of steel at all points in a concrete pipe and hence present a non-destructive method of applying the provisions of the specification.

7. GENERAL COMMENT ON THE TWO PIPE TYPES

In the course of our detailed examination of spun and Hydrotile pipes we became aware of certain characteristic differences between the two types. These differences warrant mention in this report if only to draw the attention of manufacturers to the respects in which their products could be improved.

Hydrotile pipes generally showed poor location of the steel reinforcing cage in early production but more satisfactory placement in more recent pipes. In respect of uniformity of cover over the steel they are now generally superior to thin-walled spun pipes. The single-cage barrel and collar reinforcing used in Hydrotile pipes also ensures better location of steel in the collar and better reinforcing of the pipe as a unit than does the separate collar reinforcing system frequently encountered in spun pipes.

Uniformity of concrete composition from inside to outside is another feature of Hydrotile pipes, whereas some of the spun pipes examined were found to have a considerable thickness of relatively soft sludge on the inner surface of the barrel. In one installed stormwater line examined, detritus moving down the line had completely removed this layer and exposed the steel.

Another attractive feature of the Hydrotile pipes is the dimensional accuracy and circularity of the collar sections, probably because these sections are completely enclosed in a mould during the casting operation.

On the other side of the ledger, spun pipes generally show a superior uniformity of compaction throughout their length, probably because the concrete is all subjected to exactly the same amount of compactive force for the same time, and not compacted progressively from one end to the other as in the Hydrotile process.

Spun pipes also show slightly lower levels of water absorption than do Hydrotile pipes, probably because they are made from concrete which is initially more workable and is accordingly more responsive to the compactive forces, and possibly also because the spinning process allows the use of larger aggregate size concrete with a lower intrinsic voids content.

Cavities around the steel are virtually non-existent in spun pipes and the consequent intimacy of contact between concrete and steel should provide better crack growth resistance characteristics than will be the case where cavities exist.

Obviously each type of pipe has special features which are not presently matched by the other, but appropriate attention to various aspects of concrete design and the manufacturing processes could effectively eliminate the significance of the differences. Our view, in any case, is that existing differences between top quality spun and Hydrotile pipes are not such as to warrant [illegible] discrimination in the specification.

8. OBSERVATIONS ON NZS2238

The essential nature of NZS2238 has already been discussed in Section 2 of this report, and we have agreed, with certain reservations, that the specification has in the past been satisfactory for spun pipes. We are also agreed that the current revision of the specification should be intended to apply to both spun and Hydrotile pipes without differentiation. At this point, therefore, it is appropriate to make reference to some of the specification provisions and offer recommendations for alteration or revision.

The specification requirements for workmanship, finish and uniformity of dimensions are necessary for obvious reasons and we have no comment on these. The remainder of the specification is intended to provide assurances of adequate strength watertightness and durability in pipes complying with its provisions and we have some observations to make on the tests specified for these purposes.

(a) Loading Tests

The load testing provisions of the specification currently require one reinforced pipe in every 50 or part of 50 of a given internal diameter to be proof-loaded to a specified level without development of cracks wider than 0.005". Further, if the purchaser so specifies, one pipe in every 100 or part of 100 in an order is to be subjected to testing at a higher specified load level at which no pipe shall collapse.

It is not generally realised that the ability of a thin-walled reinforced pipe to pass the cracking test is largely independent of the quality of the bond developed between steel and concrete. The steel lies roughly at the neutral axis of the stressed pipe wall and contributes nothing to strength until after the pipe has cracked. This contention has been checked and found to be valid by tests on unreinforced pipes. For given values of diameter and wall thickness of single cage reinforced pipes with the steel about mid-point in the wall section, the cracking test is accordingly only an indicator of concrete quality which is in turn a function of mix design, compaction and efficiency of curing. The cracking test thus serves the useful purpose of gauging the quality of the manufacturing process, and it has the added advantage that for pipes meeting the cracking test requirements of the specification the test is non-destructive.

The usefulness of the ultimate load test is more obscure. The ability of a reinforced pipe to carry some significantly higher load before collapsing is undoubtedly influenced by the efficiency of the steel-concrete bond, and may accordingly be reduced if the steel is very smooth-surface or is surrounded by cavities. It will also be affected by the amount and placement of the steel and the quality of the concrete. It is however debatable whether a test of ultimate load is necessary to assess the combined affect of these factors. In any case, the point of collapse is often ill-defined, and the test is almost always destructive as pipes which reach the required proof load without collapsing are usually too badly damaged to be used thereafter.

Tests performed for Ministry of Works have indicated that pipes in which the steel is poorly attached to the surrounding concrete undergo a dramatic reduction in stiffness after initial cracking. This finding suggests that a test measurement of the growth in load required to increase the width of initial cracks from 0.005" to, say, 0.010" would provide in a non-destructive manner, a sufficient indication of the quality of bond between steel and concrete.

(b) Permeability Tests

NZS 2238:1968 contains a requirement for hydrostatic testing of reinforced concrete pipes. Unfortunately, however, the test does not provide a quantitative measure of pipe permeability, and the assessment of performance is based on a poorly defined set of visual criteria.

Various specifying authorities have recognised the inadequacy of the hydrostatic pressure test and replaced it with a line permeability test in which several pipes and their associated joints are subjected to a quantitative measurement of water loss at a specified head. A test of this type has also been proposed for inclusion in the revision of NZS 2238. We consider this approach to be a valuable advance on the provisions of the old specification and a realistic method of assessing the efficiency of the jointed pipes as conduits for liquid, but before the test details are finalised certain matters should be considered.

When a concrete pipe is filled with water under pressure, the rate of flow of water into the pipe wall is initially higher than the rate of flow through it, the discrepancy being due to the water absorption capacity of the concrete. Once the pipe wall is saturated, however, the rates of flow of water into and out of it are found to be in balance, and dependent on the permeability of the concrete. If the pressure is maintained, the rate of loss of water then reduces significantly with time in a somewhat erratic manner, but after some days it is found that the rate of loss is much more stable. Only at this stage can a reliable measurement of permeability be made. In the standardisation of a line permeability test it is accordingly essential to specify a minimum time under pressure before the rate of water loss measurements are to be made.

It is generally believed that concrete permeability is proportional to pressure, and many investigations have apparently confirmed this belief. Closer examination shows, however, that the proportionality applies only to the maximum (initial) permeability. As stated above, concrete permeability reduces with time, and this behaviour is apparent at all pressure levels. Three factors have significant influence on the permeability reduction. They are internal silting in the pores of the concrete, swelling of the cement hydrate contained in the concrete, and further hydration of the cement. In most cases internal silting is believed to be the major factor.

For a particular concrete, higher pressures produce higher initial flow rates, but the rate of loss of water through the concrete ultimately asymptotes towards a level which is independent of pressure. The implication of this fact in relation to the testing of concrete pipe wall permeability is that the level of applied pressure may be chosen fairly arbitrarily but should remain constant throughout the test. There could be some advantage in the use of a high applied head, however. The reduction in water loss with time occurs more quickly at high pressures (apparently because internal silting occurs more rapidly) and the water loss reaches a stable value at about the same time as with lower heads. At high pressures, however, the component of water loss due to leakage at joints may be higher, in which case the apparent stabilised permeability may be up. A potentially useful test approach could be to apply an initial head of 5 metres (say), wait for an appropriate time and measure the stabilised rate of water loss. Increase the head then to 10 metres (say) again wait for stabilisation and measure the new rate of loss. The difference between the two measured rates of loss will provide a measure of the efficiency of the pipe joints.

In the above discussion of line permeability testing it has been assumed that the Specification for Precast Concrete Pipes is the proper place for performance requirements relating to an assemblage of pipes in a line. The alternative is to test the pipes as individual units, in which case the specification would have to incorporate stringent requirements for dimensional uniformity and circularity of the spigot and collar sections in order to provide a guarantee of watertightness of joints after assembly.

(c) Water Absorption Tests NZS 2238 contains a provision for a water absorption test to be made on samples of concrete cut or cored from pipe walls, and two arguments are commonly advanced in favour of the retention of this test. The first of these contends that absorption test results reflect the compacting efficiency of the manufacturing process and hence the strength of the pipes produced. Other things being equal this is probably true, but no relationship has been established between measured absorption values and load bearing capabilities of concrete pipes. Other factors such as W/C ratio are obviously significant in this respect, and the most direct and reliable test for overall quality is the cracking load test on whole pipes.

It is also frequently argued that the water absorption test provides an assessment of potential permeability. This again may be true in certain circumstances, but there is evidence which contradicts it. It is known, for example, that use of diatomaceous pozzolan in the manufacture of concrete pipes significantly reduces water loss in the line permeability test, yet cored specimens from such concrete pipes show water absorption values about 1 per cent higher than that of plain concrete.

Moreover, the permeability of concrete which has been subjected to steam curing only may be as much as 10 times that of concrete moist-cured at normal temperatures for 28 days, even though their water absorption values are similar. All pipe manufacturers are aware of the value of a period of moist curing subsequent to the initial steam curing.

Other criticisms may be levelled at the water absorption test. Firstly, the test procedure is open to a variety of interpretations which significantly affect the results obtained. (If the test is to be retained, the procedure will need to be amended and described in more definitive terms). Secondly, the test provides an inadequate sampling of the overall pipe production, particularly if the quality varies from pipe to pipe or from point to point in individual pipes. Thirdly the test is expensive, and is destructive to the extent that sampled pipes require repair.

In the light of all the factors discussed above, it is our considered view that the water absorption test provides little direct information on either the functional adequacy or potential durability of concrete pipes and should accordingly be discarded.

(d) Cover Tests

The NZS 2238 ~~requirements~~ requirements for minimum clear cover of concrete over steel are intended to ensure that the encased steel will be adequately protected from corrosion. Our investigations have indicated that compliance with the present specification requirements does provide adequate protection in both spun and Hydrotile pipes, but we have been surprised by the extent to which the requirements are not being obeyed.

The test method for thickness of cover presently prescribed by NZS2238 requires investigatory trenches of maximum length 4" to be cut in pipe walls. The number of such trenches is however limited to a maximum of 1 trench in every 20 pipes. With such limited frequency of examination, the detection of insufficient cover is a highly unlikely occurrence. As stated earlier, a non-destructive system of testing with a "covermeter" will allow a much more thorough examination of cover thickness, and both manufacturers and the Concrete Pipes Committee should consider the implications of the extent of non-compliance which is expected to be disclosed thereby.

We have frequently heard assurances from manufacturers of thin walled spun concrete pipes that their product has survived up to 50 years in the ground without significant steel corrosion problems. If this is the case, and we have no cause to disbelieve it, then either cover to steel was once more uniform than it is now or the importance of cover over steel is buried concrete piles has been overstressed. The second of these alternatives seems the more probable as there are numerous instances of steel corrosion in old concrete pipelines exposed above ground. This latter fact provides support for the view expressed in Section 4 of this report that pipes exposed to the air are significantly more vulnerable to steel corrosion than those in the environment below ground.

The eventual location of almost all concrete pipes is below ground in a moist environment conducive to continued curing with . consequent strength and permeability improvement. For such pipes it may be reasonable to relax the current specification provisions for cover to steel. Such relaxation could take the form of a requirement that the average cover (measured with a covermeter at every steel intercept along two opposite longitudinal lines on the pipe barrel) should not be less than the current specification minimum, but that individual points could show a cover as low as $\frac{1}{8}$" (say). Pipes intended for above ground exposure would need to satisfy a more demanding set of criteria or be treated with a suitable protective coating.

9. COMMENTS ON SUBMITTED DOCUMENTS

Minutes of meetings of the Concrete Pipes Committee and various other documents relevant to the question of the influences of voids, steel cover and concrete permeability on the durability of concrete pipes were submitted to us by the Director of SANZ.

These documents have all been carefully studied and were valuable in our assessment of the problem facing the Committee. However, several of them were purely speculative and contributed little to a positive solution of the problem, while others presented opinion which we now know to be based on false assumptions or incorrect interpretation of other technical information. Accordingly a few comments are necessary.

Several references were made in the Committee Meeting Minutes to the D.S.I.R. letter of 3 November 1971. This letter referred in general terms to the possible effect of loss of cover due to voids around steel, and some committee members apparently deduced from this that more concrete cover would be essential in Hydrotile pipe. However, since the maximum depth of cavity discovered in the early production pipes was only of the order of 0.015", and since very low cover depths (less than $\frac{1}{8}$") can apparently provide adequate protection against corrosion provided the cover is dense, it can hardly be argued that cavities in Hydrotile pipes significantly reduce the effective cover.

Other documents quoted opinion from Australia and Japan that Packerhead pipes are inferior to spun pipes in compaction and carbonation rate. The catch here, however, is that the term "packerhead" has been used in reference to all pipes other than those made by spinning or similar process, but our investigations have shown that a considerable range of quality can be produced by any one system. It is not possible to infer the quality of the product simply from a description of the manufacturing process. When Mr. L. M. Smith visited Australia in September 1972, he was shown samples of packerhead pipe of United States manufacture and considered them grossly inferior in compaction to Hydrotile pipes made in New Zealand.

An argument advanced in one of the documents submitted to us was that since spun pipes have proved their serviceability over the years, their qualities should be specified as essential minimal criteria. This argument is not tenable without the presentation of evidence that some lesser quality would not be serviceable.

In his comment on the Minority Report to SANZ, Mr. W. E. Sisson rightly drew attention to the confusion between corrosion of concrete by aggressive ground waters and corrosion of reinforcement by reduction in alkalinity in the presence of oxygen and water. He also emphasised the importance of permeability from the point of view of both these factors, but expressed the opinion that the proposed line permeability test cannot provide an index of the concrete permeability. In his view, the test measures only the total leakage from isolated weak spots and joints. We disagree on two counts. The first is the fact that the line loss asymptotes with time to a level which is largely independent of pressure. This indicates that the loss is permeability-dependent and becomes independent of pressure only because higher pressures cause more efficient internal silting. The second fact is that the stabilised rate of loss is very dependent on the surrounding environment. If the line is exposed to drying winds, the rate of loss increases. If the line is covered with wet sacking, the loss rate reduces. This indicates that the loss of water occurs mainly be diffusion through a high area of surface.

10. FINAL RECOMMENDATIONS

(a) The revision of NZS2238 should not contain requirements which differentiate between pipes made by different processes.

(b) The specification should place emphasis only on factors which directly determine the functional sufficiency and durability of concrete pipes, and should incorporate sampling frequency requirements and test methods which give reliable assessment of these factors. A sufficiently embracing series of requirements would cover dimensional accuracy, strength, permeability and steel cover.

(c) Whenever possible, tests should be non-destructive and should be applicable to whole pipes rather than to discrete sections of them.

(d) No pretence should be made at predicting durability from measurements of water absorption or the extent of cavity formation as reliable relationships have not been established. Pipes of excessive porosity (due to inadequate compaction) and pipes with inferior steel concrete bond (due to cavities or polished steel surfaces) can be detected by appropriate permeability and strength tests.

(e) The water absorption requirement should be discarded for the reasons stated earlier.

(f) If the Concrete Pipes Committee is able to accept the foregoing recommendations in principle, the revision of NZS2238 could be expedited by assigning the task of preparing a draft to a competent individual or a small sub-group of the Committee.

(g) There is considerable current interest in the manufacture of fibre-reinforced concrete products. Almost certainly this technique will ultimately extend to concrete pipe production. If possible the revision of NZS2238 should aniticipate this eventuality and make appropriate provision for it.

(Signed) L. M. SMITH, D.S.I.R.

(Signed) J. CLELLAND, M.O.W.