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DIVISION OF BUILDING RESEARCH

FAILURE OF PRESTRESSED CONCRETE PIPE AT REGINA,
SASKATCHEWAN

BY ANALYZED
ROBERT F. LEGGET

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FAILURE OF PRESTRESSED CONCRETE PIPE AT REGINA, SASKATCHEWAN†

by

Robert Ferguson Legget, M.I.C.E.

Director, Division of Building Research, National Research Council, Canada

For written discussion

SYNOPSIS

The City of Regina, capital city of the Canadian province of Saskatchewan, contracted in 1951 for the manufacture and supply of about 35 miles of 36-in. dia. prestressed reinforced concrete pipe, in 16-ft lengths, to serve as the main conduit for conveying water to the city from a newly available reservoir at Buffalo Pound Lake. Manufacture of the pipe started in a specially built plant in Regina in February 1952. Difficulties were experienced in production; a high percentage of delivered pipes had to be rejected on test. Serious failures occurred in line tests carried out in November 1952; production of pipes was stopped 1 month later.

Efforts were made to determine the cause of the trouble during the ensuing months, but on 19 June, 1953, the company supplying the pipe took legal action against the City. The judgement of the Court was appealed by the company, eventually to the Supreme Court of Canada whose decision was handed down on 2 November, 1959. While legal action was proceeding, the technical aspects of the case became widely known but it was not then possible to report upon them. This Paper has now been prepared as a record of the failure, with the objective of making known the facts of the case in the interests of contributing to the improvement of the technology of prestressed concrete, and of the design and construction of prestressed reinforced concrete pipe in particular.

ACKNOWLEDGEMENT

THE City of Regina has authorized the preparation and presentation of this Paper. It has been produced as a contribution from the Division of Building Research of the National Research Council of Canada in keeping with the Division's work in assisting the construction industry with its technical problems, and because of the many inquiries about the Regina pipe line received by the Division from many parts of the world. Some who were key members of the administrative and engineering staffs of the City when the failure took place have transferred to other positions in the years between, and so were not in a position to prepare a record such as this. The writer visited the pipe-making plant in Regina on 11 December, 1952, just before pipe production was stopped. He is therefore able to write of the process used with some first-hand knowledge

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† Paper No. 6587, Proceedings of the Institution of Civil Engineers, May, 1962.

but, to the extent that is possible, this account has been checked with those who were in intimate contact with the work at the time of the failure and is now presented as a factual record of what did take place.

2. Since the purpose of this Paper is constructive only in intent, careful study of the technical aspects of engineering failures so often leading to real advance in the art, names of responsible engineers will not be mentioned. They appear in the legal records which may be consulted by those interested. The writer knows well the careful attention that was devoted to all aspects of the original design, and of the contract operations, and also to the study of the pipe failures once they were detected. Accordingly, and at the outset of the Paper, he wishes to record his appreciation of this work, and of the assistance he has received in the preparation of this record alike from engineers and city officials. He is indebted to Miss S. Caughey, B.Sc., of his own staff, for assistance in the preparation of the Paper.

GENERAL DESCRIPTION OF PROJECT

2. Until the completion of the Buffalo Pound Lake Project the water supply for Regina was from groundwater sources. Lowering of water levels in existing wells, and lack of success in finding satisfactory additional ground supplies for development in the latter 1940's, caused the City to promote a scheme for using the South Saskatchewan River as an additional source of water¹.

4. The idea of diverting the South Saskatchewan River down the Qu'Appelle Valley dates back to 1858. Professor Hind of the University of Trinity College, Toronto, in his narrative of exploration work for the Canadian government in that year noted that such a project might prove desirable². Surveys were undertaken from 1911 to 1914 by the Irrigation Branch of the Dominion Department of the Interior in order to discover the best means of diverting the South Saskatchewan River. One of the best routes was found to be from the Elbow, which is approximately 100 miles northwest of Regina, over the Summit which is about 12 miles from the Elbow and approximately 90 ft above low water level in the South Saskatchewan River at the Elbow, and then down the Qu'Appelle Valley to the Buffalo Pound Lake. Buffalo Pound Lake is about 15 miles long and $\frac{1}{2}$ mile wide; its elevation is approximately the same as the South Saskatchewan River at the Summit. It was proposed to dam the east end of the lake in order to raise the water level 15 ft. Water would then be distributed by pipeline to Moose Jaw and Regina³.

5. Following the original surveys there were a number of studies and recommendations all of which confirmed that the South Saskatchewan River must be the eventual source of water for Moose Jaw and Regina. Actual construction was delayed, however, and additional supplies of water were located to satisfy immediate demands⁴. Following the Second World War attempts were made by the City of Regina to obtain financial assistance for the scheme from the Dominion and Provincial governments.

6. On 29 May, 1950 the Minister of Resources and Development of the Government of Canada informed the Government of Saskatchewan that if the Province and Regina, or any other city, could work out an agreement for making

¹ The references are given on pp. 19-20.

use of the water in the lake, the Federal Government would undertake a project designed to maintain an adequate supply of water in Buffalo Pound Lake⁵.

7. The Buffalo Pound Lake Project was then initiated. Its eventual cost to the City of Regina was approximately \$7,000,000, this sum including the cost of intake pipes, pumping station, a filtration plant and the pipeline to Regina. The intake is located about 800 ft from the shore in 11 ft of water. The intake pipe is a 54-in. dia. asbestos-bonded corrugated steel pipe which extends from the intake structure to the pumping station. The water flows by gravity from the lake to the wet well of the pumping station. The 2 miles of pipeline from the pumping station to the filtration plant is 42-in. dia. Where the head is high the pipe is steel with $\frac{3}{8}$ -in. walls; where the head is low the pipe is centrifugally-cast concrete. The filtration plant consists of a flash-mix tank, two upward-flow treatment units and four filters. Two pumps now deliver water to Regina through approximately 37 miles of pipeline. Chlorination has been provided for at the filtration plant⁴.

8. In the late summer of 1950 in view of the pending construction of the Buffalo Pound Lake works, the City called for tenders for the pipeline to convey water from the reservoir to Regina, the length covered by the main contract to be 187,030 ft, the diameter 36 in. Tenders were opened on 19 October, 1950, the lowest being from the Preload Company of Canada Ltd., for a prestressed concrete line. In submitting their tender, this Company stated that they were "the only one specializing in the design and construction of prestressed concrete on this continent."

9. Since they considered that prestressed concrete pipe was still in the experimental stage, the water works and project engineers for the City, and the City's consulting engineers, recommended to the City Council that the tender of the Vancouver Iron Works Ltd for a steel pipeline be accepted even though it was \$285,000 higher than the Preload Company's tender. The Preload Company made submissions to the City Council, and also prepared a printed circular which was addressed to the Councilmen and Citizens of Regina, urging the acceptance of their tender. The printed circular described the pipe to be supplied as "a high grade, durable concrete pipe, bound with the finest grade spring steel wires and is fully responsive to all requirements set out by your engineers. Further, the performance of this proposed pipe is backed up by this Company's bond for faithful performance in excess of one million dollars."

10. At its meeting on 26 October, 1950, the City Council accepted the tender of Vancouver Iron Works Ltd, for the steel pipeline. Steel proved to be impossible to obtain in the requisite quantities for the work, however, with the result that the Vancouver Company had to surrender its contract early in 1951. Negotiations were therefore reopened with the Preload Company, first for 42-in. dia. pipe and later for 36-in. dia. pipe. Two test lengths of pipe were called for: these passed the required pressure tests. Consequently, on 13 July, 1951, the City signed a contract with the Preload Company for the supply of 187,030 ft of 36-in. dia. pipe. The Company had the right to use the patented process to be applied in the production of the pipe. The City's engineers accepted statements from the Company that the prestressed concrete pipe to be supplied would be as good as, if not better than, a steel pipe.

11. The Company erected a special pipe-making plant on a convenient site in Regina and began the production of pipe in February 1952. Under the contract, pipe making was to be completed by 1 April, 1953 unless this period

was extended by the project engineer upon request of the Company. A request for an extension was made on 4 February, 1952 and was granted on 16 February, the new completion date being 15 June, 1953. Many difficulties were experienced in manufacture during the period February to December 1952. Serious failures of the pipe occurred in line tests carried out in November. The project engineer suggested to the Company's superintendent on or about 1 December, 1952, that it would be advisable to stop production until the causes of pipe failure could be determined. This was followed by a written request on 12 December. Production stopped on or about 12 December.

12. Between February and December 1952, the Company produced 4,479 pipes and 36 test pipes were made after the shutdown. Of this total only 3,087 passed the plant test, the rejection rate thus being 31%. With the exception of one pipe, the first 85 lengths were made without the use of calcium chloride but only 15 passed the plant pressure test and were accepted by the City. One difficulty encountered in manufacturing was the "slumping" of the sprayed concrete used to form the pipes. The use of calcium chloride as an admixture was therefore started as a regular procedure by the Company. Laying of the pipe was carried out by another contractor. By December 1952 four sections of pipeline had been laid with 270, 759, 549 and 12 lengths of pipe in each respectively. During the second line test serious failures occurred. The latter two sections were not tested.

13. An intensive study was therefore begun by the City and the Company, following the closure of the plant, to determine the cause or causes of the pipe failure. Both the City and the Company engaged the services of well-qualified experts. These studies examined all phases of the production of pipe. Corrosion combined with unusual splitting was found to be the cause of wire failure. Calcium chloride was found to be the cause of the corrosion, and after much controversy within the courts, the corrosion so caused was concluded to have caused the pipes to fail. It was later stated before the courts, on behalf of the City and the Company, that this conclusion was not in dispute.

14. On 1 May, 1953, the project engineer wrote to the Company on behalf of the City, giving the conditions under which pipe manufacturing could be resumed, rejecting all pipe made with calcium chloride and directing its replacement. The Company replied on 18 May, 1953 claiming that the project engineer had no right to make such demands. Further letters were exchanged and on 19 June, 1953 the Company took action against the City. This action was stayed until 6 November, 1953 pending disposition of an application by the City for the appointment of an arbitrator, in which the City was unsuccessful.

15. On 13 November, 1953, the City notified the Company that it regarded its actions as a repudiation of the contract by the Company and that the City would proceed to obtain elsewhere the necessary pipe for the project. New tenders were therefore called and although a tender for a steel-shell concrete pipeline was \$119,000 less than the lowest tender for a steel pipeline, the latter was accepted by the City. A contract was entered into with the Dominion Bridge Co. Ltd, on 19 November, 1953 and within a year all the steel pipes had been delivered and installed. The new water supply system was officially put into service on 6 May, 1955 and has been in continuous and satisfactory service since that time.

SUMMARY OF LEGAL PROCEEDINGS

16. Although it is the technical aspect of the case that has special interest for engineers, the importance of the legal proceedings warrants a summary of the relevant court actions and decisions. When the Company first took suit against the City for damages, the City replied with a counter claim for breach of contract. These cases went to the Queen's Bench Court of Saskatchewan; the judgement of Mr Justice R. T. Graham was handed down after 35 days of hearings, in November 1956. He awarded the City about \$1,285,000 damages, with costs⁶.

17. The Company, assigned in bankruptcy on 22 January, 1954, appealed the ruling of the Queen's Bench Court to the Saskatchewan Court of Appeal which, in February 1958, gave a unanimous decision upholding the judgement of the lower court⁷. The Company launched a further appeal to the Supreme Court of Canada in May 1959. On 2 November, 1959, the Supreme Court unanimously rejected the appeal, supporting the judgement of the lower court. The damages were recovered by the City from the Guarantee Co. of North America which had furnished a bond to the City for 50% of the contract price of \$2,418,517. The bonding company had also participated in the legal action, the City responding with a counter claim⁸.

18. The several legal judgements are of much interest and will doubtless prove of value as future references. Although they are naturally mainly concerned with the strictly legal aspects of the case, technical matters had inevitably to be mentioned. The following extracts from the judgement of the Supreme Court of Canada are relevant to this review of the case. Mr Justice Martland, in discussing the Company's suit said:

"I agree with the view of the Courts below that the use of calcium chloride in the manufacture of the pipes by Preload did not, in itself, constitute a breach of the specifications forming part of the agreement. It is true that calcium chloride is not mentioned in those specifications relating to materials, but the evidence shows that it was used as a part of the manufacturing process in order to hasten the setting of the core and of the cover-coat of the pipes. Its use was a part of the method of manufacture of the pipes decided upon by Preload as being proper and desirable. [The project engineer for the City] was advised by [the Company's superintendent] that it was being used. He was not asked to make a decision as to its use, but received this advice as a matter of information."

"[The project engineer] had abundant evidence to justify the rejection of pipe in which calcium chloride had been used in the manufacture when he made his decision on May 1, 1953, and it is not now in dispute that the use of calcium chloride was the cause of the pipe failures".

19. The second point at issue was the change from the steam curing as specified to the use of hot water for this purpose and on this matter the Court stated that:

"The evidence is that hot water curing instead of steam curing was used by Preload in the course of manufacture of pipe and that [the project engineer] had been made aware of this. When questioned about it at the trial, he was asked if he considered it to be a desirable change. He stated that he

did not consider it in that way. Preload wished to use it and he had no objection."

20. Summarizing his findings, the judge said:

"I have already stated my view that the use of calcium chloride was the result of a decision by Preload as to its method of manufacture. The same can be said also of the method of curing by hot water. [The project engineer] was aware of both these procedures having been adopted, but there is no evidence that at the time he should have had any reason to think that the adoption of these procedures would involve harmful results. He was not asked to make a decision as to their use. He had no reason to forbid them. This being so, I cannot see how it can be successfully contended that the City acquiesced in the breaches of the contract which resulted from the failure of Preload to fulfil the implied conditions under subss 1 and 2 of s. 16 of *The Sale of Goods Act*. All that the City was doing was to rely upon the manufacturing skill and judgment of Preload, which it was entitled to do".

On the basis of this finding, the Court rendered its judgement in favour of the City of Regina.

DETAILS OF THE PIPE

21. The pipes were to be generally 16 ft long and 36 in. in internal diameter. The shell of each pipe was to consist of concrete $2\frac{3}{4}$ to $3\frac{1}{4}$ in. thick, reinforced by steel wire circumferentially wrapped, the cover-coat being $\frac{3}{4}$ in. The wire was specified to be high tensile wire and to be wrapped under an initial tension of 150,000 lb/sq. in.

22. The process of manufacture was implicit in the design of the pipe. It involved the spraying-on of a mixture of cement and sand, under compressed air, to a thin cylindrical steel form to which were attached 24 steel wires in tension and at $1\frac{1}{2}$ in. from the mould, parallel to the axis of the pipe. The steel form was of appropriate diameter and supported in a vertical position. After curing, this core was to be wrapped with wire, the wire being drawn through a fixed die by the rotation of the concrete shell and steel form. The outer shell of concrete was then to be sprayed on in similar manner, and cured before the removal of the collapsible steel form and the transfer of the finished pipe to the storage ground.

23. A number of special features had to be included in the actual manufacture of the pipes. Since the soils in which the pipeline was to be located have an unusually high sulphate content, the outer $\frac{3}{4}$ in. of the concrete shell was specified to be constructed with special sulphate-resisting cement ("Kalicrete" being the Canadian trade name, "Type V" the American designation). The inner part of the shell was made with ordinary Portland cement conforming to Canadian standard specifications. The sand used had in it particles up to $\frac{1}{4}$ in. dia. but by normal standards, the sand mixture was generally deficient in the larger particle sizes. The cement:sand mixture used was approximately 1:3 but the process of application led to an appreciable amount of "rebound" of at least the coarser particles. In an attempt to reduce this, lime was added to the mix but the proportions of this admixture are not known. It was estimated that the final mixture in place was probably 1:2.6.

24. Calcium chloride was a further admixture introduced by the Company after initial trouble with slumping (as mentioned earlier) being added to the mixing water, presumably with the intention to limit it to 2% of the weight of the cement and in no case more than 3%. These limits had been set by the American Concrete Institute and the Portland Cement Association. The initial water cement ratio was 0.35 to 0.40. Because of the character of the controls at the plant, the exact proportions of water and admixtures are not known with accuracy. The Preload Company admitted that although the quantity of calcium chloride generally varied from 2.12 to 2.40% it sometimes ranged from 2.85 to 3.23%. Chemical analyses of the core gunite conducted at the University of Saskatchewan indicated calcium chloride as high as 3.83 of the cement weight. Any excess over the 2 to 3% range is the more objectionable where the steel is embedded in gunite rather than in traditional concrete. The proportion of cement volume, and hence of calcium chloride volume, to a unit volume of encasing material is from 50 to 100% more for the gunite than for a concrete consisting of cement, sand, and coarse aggregate.

25. The reinforcing wire was high tensile steel, its initial diameter being reduced at the die from 0.162 in. to 0.140 in. Due to conditions of storage, some corrosion of some coils of wire took place before they were used. It was estimated that passage of wire through the die increased its temperature to 325°F. Some experts in wire-drawing who were consulted on this matter suggested that the temperature might have been as high as 450°F due to imperfect lubrication. Owing to the proximity of the pipe to the die during wire wrapping and the speed of rotation (34 rev/min.) it is certain that the temperature of the wire when it came in contact with the concrete shell was well above 300°F. Minimum ultimate tensile strength was 210,000 lb/sq. in. The actual stress achieved was probably about 150,000 lb/sq. in., (made up of 120,000 lb/sq. in. at the die plus a temperature stress increase of 25,000 lb/sq. in., upon cooling).

26. Trickling hot water was used for the curing process although the original specification called for steam curing. Water drawn from the city mains of Regina was used for this purpose. In an attempt to save fuel, the water was collected in a sump and recirculated by means of a pump. (Outlet temperature was maintained at about 150°F. Water temperature over the concrete was about 140°F.) Recirculation of water was regularly continued for a full week; on some occasions, the period extended for 2 weeks. At the time of the pipe manufacture, the sulphate content of the Regina water supply was of the order of 375 ppm. Samples of the curing water taken from the pump were found to contain as much as 1,400 ppm of SO_4 . In view of the alkaline character of the water, aggravated by the use of lime in the mix, this condition represents virtual saturation of the water with calcium sulphate. The plant was kept well heated, even in the coldest weather, pipes being subjected to low air temperatures only after the expiry of the requisite indoor curing process.

FAILURE OF THE PIPES

27. The first serious wire failure was found on 22 November, 1952 in the first pipe that was removed from the second line test. When another pipe was cut to replace the failure it was also found to have corroded wires. Several more pipes revealed serious corrosion. Widespread corrosion was feared and

construction was halted to permit an investigation. As cover-coats were removed actual failure of some wires was found. Close examination showed that in many cases the corrosion had taken place on the inner side of the wires (that side in contact with the concrete core), the outer side of the wires frequently being still bright. It was further observed that the surface of the inner concrete shell was not smooth, small irregularities being sufficient in size and number to prevent the spirally wrapped wire from bearing continuously on the concrete. It was possible to detect this lack of contact with the unaided eye. Deposits of white salts were usually found in the surface irregularities.

28. In an attempt to locate corrosion without removing the cover-coat a simple electrical circuit was developed, into which could be inserted the full length of the wire wrapped on one pipe. Application of a low voltage set up a current when the circuit was complete which actuated a bell signal. Unfortunately the bell would ring at one time and then not the next with the same connexion; it sometimes failed to sound for pipes that were later found to be entirely free from corrosion. The tests with it were therefore valueless. Tests and examination of the surfaces of finished pipes were found to be the only reliable methods of finding wire failure and these continued to be used.

29. It is to be noted that, although an appreciable number of pipes made without the use of calcium chloride failed to pass the plant pressure test (§ 14), none of the pipes made without calcium chloride that were examined showed any signs of corrosion despite the fact that the same disposition of Kalicrete and Portland cement was used in all cases. On the other hand, all the pipes in which calcium chloride had been used that were examined exhibited signs of corrosion in the circumferential wires. No corrosion was noted in the longitudinal wires.

DISCUSSION

30. Despite differing views of expert witnesses before the court, and much legal argument, it was eventually accepted by both the City of Regina and the Preload Company that the use of calcium chloride was the major cause of the failures of the manufactured pipe. With this admitted, it was possible for the courts to render their judgements on the basis of law without having to define in what way the corrosion was induced so rapidly by the presence of calcium chloride. It is in the latter question that the interests of engineers will chiefly centre. From the large volume of technical evidence, the following factors emerge as having some bearing on the incidence of serious corrosion, in some cases in less than 3 months from the date of the pipe manufacture.

31. The sand-cement mixtures used for the inner and outer concrete shells were made with different types of cement. First contact of the outer mixture (made with sulphate-resistant cement) with the inner shell was made after the initial set of the latter, but at a somewhat elevated temperature and under the pressure induced by the air used for the application process. It might be expected that the mixture using ordinary Portland cement would fix (as calcium chloroaluminate) more of its calcium chloride content than the outer mixture, thus causing some chemical imbalance between the two concrete mixtures in addition to the difference between the two types of cement. If any concentration of calcium chloride developed at the interface, this might have tended to intensify the action.

32. The use in the curing process of recirculated hot water, with an appreciable sulphate content, subjected both inner and outer shells to progressively intensified sulphate action until such time as a new batch of hot water was introduced into the curing process. The measured sulphate content of the curing water was sometimes high enough to cause deterioration of concrete made with ordinary Portland cement. The "green" condition of the concrete when exposed to curing water at the temperatures used in the curing process (about 140°F) could have led to the absorption of some of the sulphate content of the water by the concrete. The possible sulphate content of concrete from this cause might have been sufficient to cause actual deterioration of the concrete; the presence of calcium chloride in the mix would certainly have accelerated any such potential failure. The use of lime as another admixture introduced further potential chemical complications which would have been dependent upon the exact type of lime used, and its expansion characteristics.

33. The phenomenon of stress corrosion would appear to have been a possible element in the failure, the temperature of the wire when applied, the curvature to which the wire was bent in application, and the irregularity of the concrete surface to which it was applied, in association with the presence of calcium chloride, providing an appropriate environment for such action.

34. After the first draft of this Paper had been prepared, a relevant paper by two members of the laboratory research staff of the Portland Cement Association (Skokie, Illinois), was published in the *Journal of the American Concrete Institute*. Some of the points referred to in §§ 29-33 are discussed in this Paper, to which reference may therefore be made for a more detailed discussion of the research implications of the Regina failure⁹.

CONCLUSION

35. For a number of reasons, not the least of which is that the manufacturing process used at Regina is covered by patents, it is improbable that the same combination of circumstances will ever recur in connexion with the production of a prestressed concrete pipeline. The magnitude of the failure, however, and the rapidity with which the corrosion of the reinforcing wire was found to develop, lend special interest to all possible contributory factors to the failure. The list just presented, although not exhaustive, is at least suggestive of some avenues of needed research if the art of prestressed concrete design and construction is to advance. The pipes manufactured for the pipeline were not all destroyed, and so a fair number are still available for inspection by any interested in the research aspects of this case. Some were purchased by the City of Regina and are now in use throughout the municipality as culverts.

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The Paper was received on 4 July, 1961.

Written discussion on this Paper should be forwarded to reach the Institution before 15 July, 1962 and will be published in or after November, 1962. Contributions should not exceed 1,200 words.—SEC.

DISCUSSION

on Paper No. 6587, Proceedings, May 1962

Failure of prestressed concrete pipe at Regina, Saskatchewan

by

Robert Ferguson Legget, M.I.C.E.

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Failure of prestressed concrete pipe at Regina, Saskatchewan

by

Robert Ferguson Legget, M.I.C.E.

Dr Jacob Feld (Consulting Engineer, New York), wrote that open discussion of failures, with presentation of all pertinent observations and physical data, was a professional duty, more so than the description of glorious successes. Much more could be learned, as a warning of the limitations for safe use of material combinations, from a Paper like the Author's, than from volumes of detailed reports on structures that showed no distress. Of course, closer scrutiny of many structures might uncover some worthwhile information.

37. In his recent professional work, Dr Feld had been required to inspect and diagnose the cause of several structural failures. Difficulties with similar reinforcing wire, similarly installed on a vertical concrete cylinder, were the subject of one such investigation. Actually, the difficulties were brought to sharp attention by the collapse of a 2.5-million-gallon sludge-holding tank, at 5.45 a.m. on April 21, 1961, when 1.6 million gallons came out as a surge wave and overturned three railroad cars.

38. The public authority concerned agreed that the information collected to explain the cause of failure was sufficiently valuable to warrant public disclosure. Summary articles on the general heading 'Corrosion wrecked prestressed tank', followed by numerous discussions appeared in *Engineering News-Record* from the issue of 2 November, 1961 until Dr Feld's reply on 25 January, 1962. A summary of the findings would be of interest, since the same type of wire failure occurred in the absence of the proximate causes listed by Mr Legget.

39. Located at two separate disposal plants, the tanks were set in batteries of eight in two lines, spaced somewhat apart, with closure walls around a large operating room. The outsides of the tanks were covered, for architectural reasons as well as for heat insulation, by a brick cladding laid with 2-in. cavity. The inside dimensions of the tank were 103 ft dia. by 35 ft high in one plant, and 118 ft by 32 ft in the other. Failure at 10-year age occurred in a section of the tank exposed to the north-east, the direction of maximum driving rain. Some difficulty was being experienced with roof drainage leaking into the cavity wall. The coping was not prestressed although built as a vertical continuation of the tank barrel, and relative contraction between barrel and coping cracked the contact at roof level and fractured the waterproofing.

40. None of the concrete nor the gunite contained any calcium chloride or any other addition to the mix. The collapse exposed the condition of the reinforcing in that section. Later demolition of the remainder of the tank permitted close inspection of the reinforcement and comparison of conditions in the portions exposed to the temperature changes; rain leakage and possibly salt air moisture had penetrated the brick cladding and the gunite covering the wires, as against the interior exposure of controlled fairly uniform temperature and humidity. The operating equipment and metal conduits in the room showed no undue rusting or corrosion.

41. Before the collapse of the tank, there were several warnings over the years that the wires were being altered by corrosion, when the gunite covering, within the room

* *Proc. Instn civ. Engrs*, vol. 22, May 1962, pp. 11-20.

areas, cracked and spalled. The cause in some instances was found to be complete disintegration of the aluminium connectors used to splice the ends of the wires as run off the spools. Other areas were close to pipe sleeves penetrating the tank walls, while others were not explainable from such causes. The wires found to be rusted and pitted were cleaned and red-lead.

42. Careful surveys of possible electrolysis were made with negative result; no stray electric currents could be detected.

43. After the failure and demolition, it was clearly shown that:

- (a) The concrete was sound and dense, the sludge liquid had not penetrated even 1/16 inch.
- (b) All embedded normal reinforcing steel was sound, with normal rusting on the surface and no loss in area.
- (c) The vertical post-tensioned steel wires, 0.160-in. diameter, located in grooves in the 12-in. wall thickness, on the inner face and later filled with mortar to give a 3/4-in. protection from the sludge, were in perfect clean and smooth condition.
- (d) Galvanized metal slotted anchors set in the outer gunite covering for holding the brickwork were considerably eaten away by corrosion and rust. In some points, the back of the slot had been in contact with the outermost horizontal hoop wires.
- (e) The horizontal hoop wires, stressed by pulling a 0.160-in. wire through a die to a 0.140 in. dimension, were severely corroded, more so on the outer area, with practically no aluminium connectors found intact and with many wires severely reduced in area or completely parted. Only a few wires, not over 10% in the interior wall area were found clean and smooth. Some of these, when bent, were found to have internal longitudinal streaks of rust and a tendency to split with shiny surfaces. No clean conditions were found in the wire which fell away from the collapsed portion, but here a complete examination was not possible since the rubble was considerably mixed up.

44. Exposure of some wires in tanks which did not fail also showed longitudinal splitting of the wire as well as serious rust conditions. All of the remaining tanks were at present being provided with welded steel plate liners designed to take the full lateral pressures.

45. Corrosion and erosion of the wires caused sufficient loss in area to permit failure, purely from static liquid pressure. The proximate cause, discounting the added loss in strength from the disintegration of the connectors, electrolytic travel of metal at contact of dissimilar metals, oxidation from vapour exposure and from seepage through the wall covering, was considered to be the phenomenon loosely called stress corrosion. The wires had been re-heated during the stressing, without subsequent annealing. The curvature was formed by a sharp change in direction of pull causing large differential stress in the parallel fibres. It seemed quite likely that the disturbance of the interlocking surfaces of the atomic structure (these contacts were called Fermi surfaces in solid physics) opened ultramicroscopic discontinuities which permitted electrolytic metal transfer and explained the longitudinal splitting. Once the wire was split, corrosion set in; no environment except a perfect vacuum would be perfect protection.

46. Much could be learned from these costly and sometimes unfortunately hazardous incidents. Each taught a lesson of what not to do. Several such examples were contributed by Dr Feld as discussions to the 4th International Prestressed Concrete Congress, Rome, 1962 and the elaboration of detail on this incident would appear in its Proceedings.

Dr N. Stutterheim (Vice-President, South African Council for Scientific and Industrial Research) wrote that the Author was to be congratulated for the clear and concise summary of the circumstances surrounding the failure of pipe-sections, as produced for the

City of Regina during 1952. The paper was of particular significance and importance to civil engineers and concrete technologists, as well as to all authorities concerned with the use of large diameter prestressed-concrete pipes. It was unfortunate that, as a result of the protracted litigation which made the technical evidence relevant to the case *sub judice*, this important information was only made available, first by Monfore & Verbeck⁹ and now by the Author, many years after the event.

48. It is clear from the record that the technical evidence to the effect that calcium chloride played the key rôle in the corrosion of the reinforcement, was so strong that it was accepted by both litigants as well as by the various Courts. However, from the Author's paper it was clear that it could not be concluded that calcium chloride, even in relatively large concentrations, caused corrosion of all steel exposed to a cement matrix in which this chemical was present. The Author stated specifically that the longitudinal prestressing wires were not subject to corrosion, and that in the case of the circumferential wires, the outside surfaces (those away from the core) were still bright, in marked contrast to the inside surfaces of the same strands.

49. These statements were significant if one wanted to learn one important lesson from this failure. It was Dr Stutterheim's considered opinion that, although the presence of soluble chlorides in concrete predisposes the steel to corrosion, there were physical and chemical conditions in the concrete or in the cement paste surrounding the steel which also had a material influence. For instance, if the concrete or mortar surrounding the steel was of high quality (low water cement ratio, low permeability), the presence of calcium chloride would not necessarily lead to corrosion of steel, and certainly not in the short time found at Regina. On the other hand, corrosion would take place rapidly if the cement paste at the surface of the steel was fairly permeable, or was not bonded to the steel surface, and the elements required for corrosion to proceed at some speed, viz. moisture, calcium chloride and oxygen, were available.

50. It was therefore not without significance that the corrosion was found to have occurred in the region of contact between the steel and the core. Since the wire was wrapped onto a hardened concrete core, and subsequently covered with the external protective coating, it was inevitable that the sprayed protective mortar would not always have covered the steel around its whole circumference. The contact area between core and wrapped wire, being under high pressure, could not be penetrated by cement particles; only cementitious material in liquid phase could reach this area. In these regions therefore, there would still be unbonded steel surfaces, and the physical and chemical requirements for inhibiting corrosion of the steel would not exist.¹⁰ The aqueous solution present in the fresh cement paste, containing also chloride, would be drawn into those areas by capillary forces, and so bring about rapid corrosion.

51. Corrosion on the inner surfaces of circumferentially-wrapped prestressing steel on a hardened concrete core had been observed by Dr Stutterheim, even in cases where no calcium chloride was added to the concrete or mortar, though the process was then relatively slow. If calcium chloride were present, it would be logical to conclude that the risk would be very much enhanced; the Author's observations on the Regina pipe bear this out.

52. The conclusions to be drawn from this aspect of the Regina pipe failure therefore appeared to be:

- (a) The use of calcium chloride in all concentrations should be prohibited in circumferentially-wrapped prestressed concrete pipes, tanks, and structures of a similar nature.
- (b) The whole process of wrapping steel on hardened concrete with subsequent covering by a protective layer, requires intensive study, with a view to eliminating the risk of corrosion, even if no corrosion-promoting electrolytes like calcium chloride are added, because such electrolytes could subsequently penetrate to the steel from the atmosphere (sea air), ground, or the liquids in the container.

Mr S. McConnel (Retired civil engineer) wrote that in view of developments in prestressed concrete pipe lines on the Continent, it seemed strange that technical knowledge still took so long to cross the Atlantic. Over 50 years ago reinforced-concrete pipes with a steel interlining were used in Belgium and in one case at Norwich. In 1917 about 250 miles of centrifugally-cast pipes were employed in an irrigation scheme in Southern Italy, while French engineers started prestressing concrete pipes about 30 years ago. Since that date a considerable number of successful schemes had been carried out. Unlike the American ones these dispensed with a steel interlining. Attention was drawn to the construction of a 150-mile pipe line near Mombasa, Kenya, in which a reinforced-concrete core with embedded prestressed longitudinal wires was centrifugally cast, wound with prestressed wire and then protected by an external coat of mortar applied mechanically.

54. The work was carried out to a considerable extent by African labour, without any serious difficulty and last year while in Mombasa the writer was informed that maintenance had been practically negligible. In this case as at Regina, steel pipes were ruled out of court owing to the impossibility of obtaining steel. To proceed with the construction of a pipe line where the percentage of rejected individual pipes was as high as 31% seemed to be, to express it mildly, most unusual. It was well known that calcium chloride caused corrosion in steel and the use of a water heavily dosed with sulphates should also have been regarded with misgiving. The publication of this Paper would, however, in no way lessen the confidence of many engineers in the efficacy of prestressed non-cylinder pipes which have already proved so successful outside the American continent.

Dr C. E. Bird (National Building Research Institute, South Africa) wrote that the Author was to be congratulated on his most balanced summary of a complex and involved problem. The failure of prestressed-concrete pipes at Regina and the subsequent litigation had focused the attention of corrosion and concrete technologists on the various problems concerning the construction of sound prestressed concrete pipes in which the steel is not subject to corrosion. The following comments might be of interest.

56. It has been fairly well established that corrosion of reinforcing is enhanced by:

- (a) Oxygen differential cells,
- (b) variation in salt concentration, and
- (c) differences in the pH of the material surrounding the steel.

(a) Oxygen differential cells

57. Recent tests by the National Building Research Institute had shown that reinforcing steel surfaces in contact with salt-free fresh concrete, i.e. uncarbonated concrete, were subject to rapid anodic polarization. Thus, owing to variation in cover thickness and permeability of the concrete, no differential aeration cells could operate. With the uniform addition of 2 per cent sodium chloride by weight of the cement, however, the anodic polarization curve became much less steep and steel surfaces to which oxygen diffusion was restricted became permanently anodic. This may have accounted for the preferential attack on the inner surfaces of circumferentially-wrapped prestressing steel in the Regina pipes; the outer surfaces having been nearer the pipe surface probably received cathodic protection.

(b) Salt concentration

58. When 2 per cent sodium chloride by weight of the cement was added in an attempt to obtain a uniform salt concentration, it was found that this condition was in fact not achieved; the concentration was highest near the casting surface, probably due to transportation of the salt by water moving to the surface where evaporation took place.

59. If this phenomenon occurred in the Regina pipes the salt content at the outer surface of the core would have been higher than at other points in the pipe. The

portions of the spirally-wrapped wires in contact with the core would then have been in contact with a higher concentration of calcium chloride than those portions against the outer layer of cover concrete. This variation in salt content on the inner and outer areas of the prestressing wires may have contributed to the rapid deterioration of the portions of the wires in contact with the core. Moreover, the addition of calcium chloride reduces the overall electrolytic resistance of the concrete resulting in increased corrosion currents.

(c) *Variation in pH.*

60. The surface skin of concrete carbonates on exposure, especially at elevated temperatures. This reduces the pH near the surface. The reaction is soon stifled, however, owing to the sealing effect of the formation within pores of the more voluminous carbonation product, CaCO_3 . Although no information was available to substantiate this, it was possible that the circumferential wires may have been in contact with a carbonated core surface on the inside and with an uncarbonated concrete with a high pH on their outer surfaces. This differential pH condition could also have contributed to the attack on the inner surfaces. This type of corrosion could take place even in the absence of salt although at a much reduced rate.

61. It was extremely difficult, at this stage, to ascertain what relative effects the factors mentioned above might have had on the failure of the Regina pipes. A consideration of these factors may, however, assist concrete technologists in appreciating the importance of the various factors involved in the corrosion of prestressed reinforcing.

The Author, in reply, wrote that the contributions of Dr Feld, Dr Stutterheim and Dr Bird were greatly appreciated. They added much useful information not only with respect to the various phenomena that were associated with the Regina failure, but also in relation to more general features of corrosion in prestressed concrete structures.

FIG. 1: PORTION OF FAILED PIPE

63. The opinions of Dr Stutterheim and Dr Bird as to possible causes of the corrosion of the wire agreed so closely with those of the Author and his colleagues that it remained only to say that further examinations of specimens of failed pipe made since the Paper was written had confirmed the invariable existence of corrosion of the circumferential wires where in contact with the core, and not on the side covered by the shell. Some 'splitting' of wires was also observed.

64. If only for the record, a photograph (Fig. 1) was submitted of a portion of one of the pipes which failed badly, following removal of a part of the shell. The irregularity of the surface of the core on to which the circumferential wire was wrapped was clearly evident.

65. The Author greatly regretted if any statement in his Paper was such as to give any grounds for Mr McConnell's suggestion that 'technical knowledge still took so long to cross the Atlantic', presumably from east to west, unless the reference was meant to apply to the delay in the submission of the paper, due to legal restrictions as explained in the text. Correspondingly, the Author could find nothing in what he had written to give any warrant to Mr McConnell's further implication, in his closing words, that prestressed concrete pipe had proved to be generally unsatisfactory in North America. The failure at Regina was, fortunately, unique in North American practice. It had been described with constructive intent only so that engineers on both sides of the Atlantic could benefit from the study that had been made of the unusual failure, with possible ultimate benefit to the advance of prestressed concrete pipe design and construction in general.

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