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An investigation into the cause of cracking in a reinforced concrete silo containing cement*

by R. E. Rowe, M.A., A.M.I.C.E.

Contribution by J. E. Guest

(*Matthews & Mumby Ltd*)

The results of the tests described in Mr Rowe's paper and the conclusions drawn from them are similar to those reported by Reimbert[1]. As may be expected, the magnitude of the dynamic increase in pressure varies with the nature of the contained material and the methods adopted for filling and emptying a silo. Reimbert's tests were carried out on steel silos containing grain and the greatest increases in pressure were recorded while the silo was being emptied. Previously, in 1943, the same author had proposed a method of calculating the pressures, stated to be more accurate than Janssen's method, and he has also suggested the use of a cylindrical device extending up the centre of a silo through which the contained material can be emptied without any significant increase in pressure being recorded.[2] If the proposed theory is applied to the cement silo, the calculated pressures appear to lie roughly half-way between those predicted by Janssen's method and the maximum measured pressures as shown in Figure 8 of Mr Rowe's paper.

Contribution by H. Holman, M.I.Struct.E.

(*Henry Pooley, Consulting Engineers*)

Mr Rowe's article is very timely, particularly in view of the increasing use of air-slides for the extraction of materials from silos and the increasing use of air for mixing and circulation. The need for further investigation is amply brought out in this paper, but I feel it would add to the knowledge of internal friction if figures could be given for the fineness and specific surface of the cement with which the silo was filled during the test since the angle of internal friction will obviously vary greatly with the specific surface and particle size. Further, it would be interesting to learn the mode and rate of filling of the silo, whether by pneumatic pumping or by mechanical screw conveyor, and the rate of emptying, because these might well have a bearing on the curves during filling and emptying.

As a matter of interest, Figure 8 of the paper is reproduced (as Figure I) with the addition of two further curves, but with all curves based upon the assumption that the density of cement at any point was consistently 90 lb/ft³. The first curve is based upon Janssen's formula, but the factors used are $k = 0{\cdot}40$ and $U' = 0{\cdot}55$ which were reputedly found to give pressures approximating more closely to the figures obtained from actual tests carried out by the Iowa Engineering Experimental Station[3]. The second curve is based upon Airy's formula, $U = 0{\cdot}316$ and $U' = 0{\cdot}554$, and this curve appears to give results closest to the pressures found on test. Indeed, if the excess pressures anticipated during filling and emptying are allowed for, the Airy curve would almost meet the designer's need.

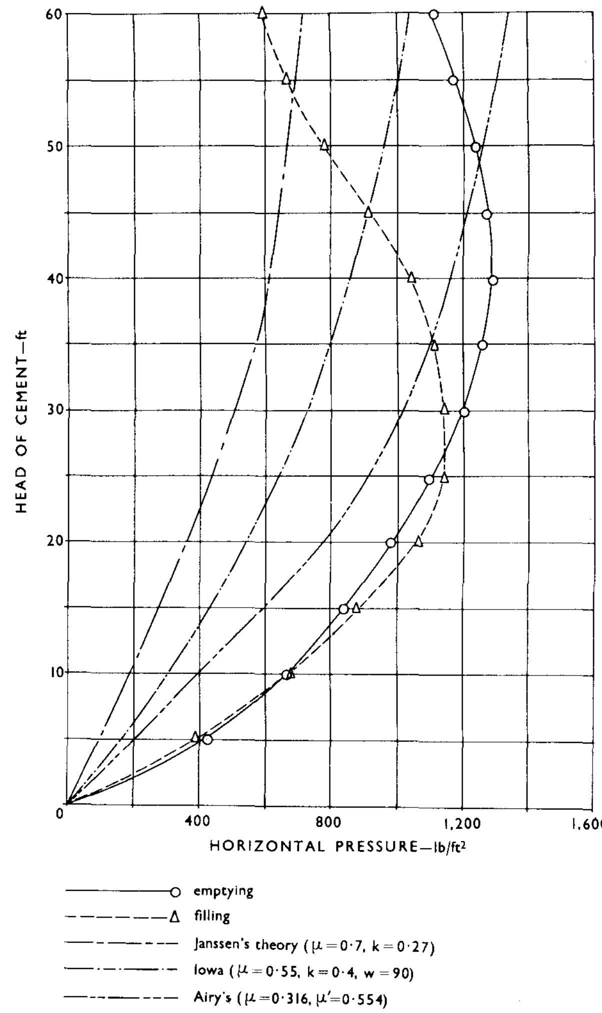

Figure I

There is, however, a marked change in direction of the test curves at 27·5 ft during emptying and at 40 ft during filling, and the curve for emptying is a straight

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line from about 8 ft down to zero. Could this straight line not be accounted for by the aeration of the cement by air introduced at the air-slides? If so, the pressure of the air indicated is just over 4 lb/in^2 with cement liquefied to 75 lb/ft^3, but this does not allow for the fall in pressure due to the air passing out of the silo with the cement. It would be interesting, therefore, to learn of the actual air pressure on the underside of the air-slides during the test and also the volume of air available from the compressors.

If air was introduced at higher pressures, but in insufficient volume to aerate the entire volume of cement in the silo, funnelling could conceivably take place to a greater height than 8 ft, the exact height depending upon the pressure, and the liquid pressure from such a column of cement at 75 lb/ft^3 would add to the normal calculated pressures due to the head of relatively dead cement. Moreover, such a column of aerated cement might well be situated adjacent to the silo wall and the moments thus arising in the wall could well act together with moments set up in only one portion of the circumference in areas remote from relatively dead cement (as experienced during the test) because of the temperature gradient in the wall due to hot cement. This might account for the extremely variable results obtained on test.

The effect of air pressure and aerated columns is of particular interest in view of certain Continental practices. Air is sometimes used for the air-slides at a pressure of 2 atm for silos 60 ft high and of 3 atm for silos 90 ft high. The air volumes available at these pressures are usually insufficient to aerate more than about 15% of the whole silo content at the appropriate head, but destruction of the entire internal friction could take place if " circulation " of the material in the silo occurred, particularly if the air was left on with the outlet valves of the air-slide closed. Moreover, incorrect operation of a battery of compressors might provide a much greater volume of air accidentally, the effect of which would be dependent upon the area of air-slide with which the silo was provided.

It is appreciated that British and American practice is to extract cement with pressures of about 3–4 lb/in^2 only and this may have been the practice with the silo tested by Mr Rowe.

The paper does not mention the significance of the large difference in vertical pressures on the walls of the silo depending upon the ultimately correct curve for maximum horizontal pressures, and this might be very important when the ring type of foundation is employed. At the same time, if quiescent cement in a full silo was still found to give horizontal pressures approximating to Janssen's formula, the vertical pressures would then be a maximum requiring the designer to take care of the worst of both worlds.

Mr Rowe's comments on my observations would be most welcome, even though everything I have said may not apply to the silo in question.

Contribution by E. C. Ruddock, B.A.I., M.Sc.(Eng.), A.M.I.C.E. (*College of Technology, Belfast*)

On the basis of his test results, Mr Rowe rejects the Janssen formula for lateral pressure in silos and substitutes a formula which may be written

$$p_h = \alpha w H$$

where p_h = normal pressure on vertical wall at any level

H = head of material above this level

w = average density of material above this level

α = an empirical multiplier derived from the maximum pressure observed under the head H in the tests.

It is incorrect to call α " the Rankine coefficient " and to equate it to $(1-\sin\varphi)/(1+\sin\varphi)$, which is the theoretical ratio of principal stresses in a semi-infinite cohesionless mass. It may be assumed that compression of the material near the bottom of a silo allows sufficient downward movement of the mass of the material to result in the greatest possible friction between the wall and the stored material. Thus there is a large tangential stress on the wall, and the normal stress p_h cannot be a principal stress. Furthermore, because of the transference of load to the wall, by friction, the vertical pressure on horizontal planes must be less than the " hydrostatic pressure " wH.

The formula proposed has, therefore, no theoretical basis, and the varying multiplier α is only known for the 30 ft diameter silo in which pressures have been measured.

A rational method of design for other diameters and shapes can be evolved, however, by the application of Mr Rowe's results to the Janssen formula. For estimation of the pressure at infinite depth during filling or at rest, the Janssen formula is theoretically exact and well supported by experimental evidence.[2,4] This pressure is given by

$$p_h = \frac{wR}{\mu}$$

where w = density of material at infinite depth

R = plan area/perimeter of silo

μ = coefficient of friction between wall and contained material.

By equating wR/μ to Mr Rowe's maximum observed pressure, we obtain

$$\frac{95 \times 7{\cdot}5}{\mu} = 1{,}300$$

$$\text{or } \mu = 0{\cdot}55$$

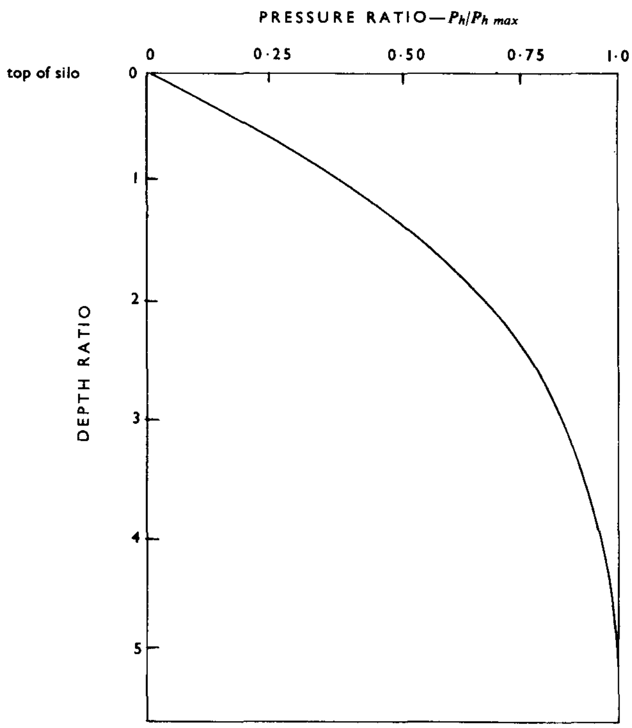

Figure 11: Variation of design pressure ratio ($p_h/p_{h\,\text{max}}$) with depth ratio (depth/hydraulic radius).

For any concrete silo containing cement, the maximum lateral design pressure would be

$$p_h = \frac{wR}{0{\cdot}55}$$

$$= 1{\cdot}82wR$$

Since Mr Rowe's maximum pressure was recorded with a head of 40 ft in a 30 ft diameter silo, it must be assumed that maximum lateral pressure is developed at all levels more than $1\frac{1}{3}$ × diameter (i.e. about $5R$) below the top of the silo. For depths less than $5R$, the curve of design pressures should have a shape similar to that of the curves based on Mr Rowe's test results. Such a curve is shown in Figure 11.

In this method of design, one is assuming the action on the whole circumference of the wall of a pressure equal to the maximum measured by Mr Rowe under the appropriate head of cement. The actual pressures measured at each head varied widely (from the maximum down to 30% of the maximum at 20 ft head, and from the maximum down to 40% of the maximum at 40 ft head), as shown by his Figure 6. This appears to be due to variation in the depth of the cement round the circumference of the silo, and can, presumably, be avoided by feeding the cement in at the centre of the roof slab. If this is not possible, serious consideration must be given to the circumferential bending moments induced in the wall by non-uniformity of pressure.

Measurements of pressures in silos have sometimes indicated pressures during emptying which by far surpass those exerted during filling and are of unpredictable magnitude.[2,4] These pressures are not fully understood, but their occurrence is linked with the discharge of certain materials by certain methods. It is reasonable to conclude from Mr Rowe's results that such pressures do not occur in a concrete silo discharging cement by air-slide. Nevertheless, he is right to call for tests on other silos used for storing cement. Such tests will be particularly valuable where the disposition of air-slides, or other details of the discharge, differ from those in the silo already tested.

Reply by the author

I am grateful to Mr Guest for bringing to my attention the experimental work of Reimbert. Since I wrote the paper some experimental work has been reported from Russia[5] which indicates pressures of the order of 1·5–2·2 times those given by the Janssen formula, such as were obtained during emptying.

With regard to Mr Holman's contribution, a mechanical screw conveyor was used to fill the silo and the time for filling and emptying the silo to the levels stated in the paper varied considerably, being up to 14 h for filling, and up to 19 h for emptying. The pressure of the air used in the extraction process was 2–3 lb/in^2. Mr Holman's remarks on the possibility of local pressures due to fluidization of the cement are very relevant to all silos in which extraction by air-slide is used. Such local effects may introduce considerable bending stresses in a horizontal plane and need further investigation. In the design of the air-slides, it would seem desirable to provide masks to ensure that air is introduced only in the central area of the silo: this would probably have a similar effect to that mentioned by Mr Guest when he referred to Reimbert's suggestion of a cylindrical device, centrally placed, to reduce the pressure on extraction.

The vertical pressures on the foundation ring beam will depend on the behaviour of quiescent cement, as Mr Holman states. Unfortunately, it will be necessary to carry out tests over some considerable period before it is possible to define the full range of the horizontal pressures and hence of the vertical pressures. It is hoped to install pressure gauges in a silo, to be constructed in the near future, to obtain this information.

Mr Ruddock states that it is incorrect to call α " the Rankine coefficient ": I agree with him. The variability of the behaviour of the cement, as indicated by Figures 6 and 7, made it necessary to adopt some method of considering the results in a systematic manner and the use of " the Rankine coefficient " was convenient. The suggested rational design method is in my opinion, liable to considerable inaccuracy by virtue of the large variation in density obtaining in a silo, and the associated effect on the angle of internal friction between the wall and the contained material. A fundamental study of the behaviour of cement would be of great assistance in clarifying this point.

The interest that has been aroused in the true behaviour of the stored cement in silos, as indicated by the discussion to my paper, may be attributed largely to the initiative of Messrs Oscar Faber and Partners in appreciating the need for some fundamental work on this subject and in organizing the subsequent testing.

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