

Blending Silo Failure Investigation for A Kenyan Cement Factory

Case Study



**CDC****Construction Diagnostic Centre Pvt Ltd.****CDCPL Websites:**<http://www.ndtconcrete.net/><http://www.ndtconcrete.net/>**Industry:**

Consultancy & Construction Material Testing
Laboratory

Region: Global**CDCPL Solutions:**

- Non Destructive Testing
- Structural Condition Survey (Structural Audit)
- Structural Restoration Consultancy
- Heritage Structures Conservation Consultancy
- Forensic Engineering Consultancy
- Concrete Quality Control and Audit
- Corporate Training for Construction Industry
- Research & Development

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A blending silo with dimensions, 20m diameter and 84m height used for storing cement collapsed at a leading Kenyan Cement factory. CDCPL was commissioned to carry out a forensic investigation to assess the probable causes of the collapse. CDCPL's investigation revealed various issue like large variation in concrete strength, design errors, construction errors, utilizations errors, lack of routine inspection and so forth. This case study entails the details of the nature of damage and investigation methodology applied by CDCPL to conclude the factors causing the collapse of the silo.

Forensic Audit:

CDCPL deployed engineers to conduct the forensic audit at the site of the silo collapse in Kenya a few days after the incident occurred.

CDCPL's investigation activities were segmented into,

1. Site level data/information gathering, structural audit
2. Structural audit
3. Perform non-destructive tests
4. Re-analyze the silo to determine probable cause of failure.

Following table highlights the investigation activities carried out by our team to determine the exact cause of the collapse.

Data/Information Gathering	Structural Audit	Non-Destructive Tests	Blending Silo Failure investigation
<ul style="list-style-type: none"> ➤ Study of Structural, Architectural, and machinery loading drawings ➤ Information gathering pertaining to, <ul style="list-style-type: none"> • Type of raw materials used in construction. • Construction data and sequences • Quality control norms and records. • Test reports • Soil Investigation Report • Concrete Mix proportions including Raw material data • Construction Data • Concrete / reinforcement data ➤ Observations made during collapse 	<ul style="list-style-type: none"> ➤ Detail inspection of the entire structure ➤ Photographic survey ➤ Physical measurements of thickness, sizes of members ➤ Physical measurement of tilts, sags, deflections ➤ Assessment of actual loading at the time of failure ➤ Assessment of visible structural distresses on disturbed and undisturbed areas, members and materials 	<ul style="list-style-type: none"> ➤ Ultrasonic Pulse Velocity test – Direct, Semi- direct & Indirect Methods ➤ Rebound Hammer Test ➤ Core Test ➤ Carbonation Test ➤ Chloride & Sulphate Content test 	<ul style="list-style-type: none"> ➤ Analyze the data collected from the site to assess the probable cause of failure ➤ Analyze the NDT results ➤ Re-check the design calculations of the entire Silo structure as per original design assumptions ➤ Re-analyze the entire structure using actual site data, measurements, concrete strengths assessed by ND test ➤ Assess the probable cause of Silo failure based on all above information.

Observations:

Visual Observations

- Complete collapse of the blending silo above the junction of wall and bottom conical slab at 19.5 – 20.0m level.
- Major portion of the Silo observed collapsed on the North and rest of the concrete wall including the stored material collapsed on other side.
- No visible cracks noticed on the remaining RCC wall.
- Clear cover to the wall reinforcement was observed to be about 75 to 100 mm.
- Yielding of the reinforcing bars not observed. Majority of the bars were either noticed to be cut like a shear failure or opened out at splice locations.
- None of the reinforcing bars were noticed to have any sort of corrosion.

Technical Observations

Blending Silo	
Max. Storage Capacity of Silo	17967 Cubic meter
Max. Design Weight of material inside Silo	19764 Tons
Density of material from mechanical point of view	1.1 (estimated value)
Max. Design Weight of material inside Silo	25154 Tons
Density of material from structural point of view	1.4(estimated value)
Thickness of RCC Wall below Hoper Support	850 mm
Thickness of RCC Wall of Storage Silo	475 mm
Average thickness of Top Slab of Silo	150 mm
Average thickness of Inverted Cone	500 mm
Internal Diameter of Storage silo	20.0 m
EL. of Cone Bottom above GL	17.56 m
EL. of Top of Top Slab above GL	83.50 m
Max. Level of Filling below Silo Top	0.15 m
Height of av. Material Storage from Cone Bottom	65.31 m

Concrete / Reinforcement data	
Design Strength as per design drawing	30 N / Sqmm
Design Strength as per site mix	25 N / Sqmm
Maximum Compressive strength of cube	30 N / Sqmm
Design Strength of reinforcement as per design drawing	460 N / Sqmm.
Minimum 0.2 % proof tensile strength of reinforcement	465 to 560 N / Sqmm.
Minimum % Elongation of reinforcement	16 to 25 %

Note: The strength of site concrete was predicted by carrying out a regression analysis on combined NDT methods – Rebound Hammer Test, UPV Test and Core test.

Observations made during collapse

- Crack was first noticed at 0700 hrs.
- It took 7 hours for the silo to collapse after the crack was noticed
- The crack was associated with spalling of cover concrete and the reinforcement was exposed
- A bulge was observed at 20 to 30 m height
- Just before failure, concrete began to peel
- The stored material oozed out from the horizontal crack for few seconds just before collapse.
- Wall bulged more
- A wide and long horizontal circumferential crack developed within a fraction of seconds and the entire silo above 20 m level collapsed.
- No vibrations noticed in the Silo or the pipes / Ducts / adjoining Structures connected to the Silo before the collapse

Structural Data

Silo Data	
Total capacity of Silo	20,000 Tons
Maximum capacity the Silo was filled till date	18000 Tons
Height / capacity the silo was filled on the day of collapse	Up to 7 m from top 17,000 Tons
Strata the silo was resting on?	Rock, Limestone Bed
Bearing capacity of soil assumed in design	40 T/m ²
Depth of foundation bottom	3.5 m

Non-Destructive Tests/ Other Tests

CDCPL conducted non-destructive tests including core test on all components of the silo including raft, remaining wall portion, conical slab & collapsed silo wall.

CDCPL performed the following tests on the structure:

- Rebound Hammer Test
- Ultrasonic Concrete Test
- Concrete Core Cutting
- Carbonation Test
- Chloride & Sulphate Content

The qualitative assessment of concrete quality was done based on the following table -

Gradation of Quality of concrete (as per CDC) Direct & Semi-Direct velocity Km/Sec.				
Quality of Concrete	< 15 Mpa	20 to 25 Mpa	30 to 35 Mpa	> 40 Mpa
Excellent	More than 4.000	More than 4.400	More than 4.600	More than 4.900
Good	3.500 to 4.000	3.750 to 4.400	3.900 to 4.600	4.150 to 4.900
Medium	3.000 to 3.500	3.400 to 3.750	3.600 to 3.900	3.800 to 4.150
Doubtful	Less than 3.000	Less than 3.400	Less than 3.600	Less than 3.800

Gradation of Quality of concrete (as per CDC) Indirect velocity Km/Sec.				
Quality of Concrete	< 15 Mpa	20 to 25 Mpa	30 to 35 Mpa	> 40 Mpa
Excellent	More than 3.500	More than 3.900	More than 4.100	More than 4.400
Good	3.000 to 3.500	3.250 to 3.900	3.400 to 4.100	3.650 to 4.400
Medium	2.500 to 3.000	2.900 to 3.250	3.100 to 3.400	3.300 to 3.650
Doubtful	Less than 2.500	Less than 2.900	Less than 3.100	Less than 3.300

Note: Quality gradation as per IS – 13311 (part-1)- 1992 is found valid only for M-15 grade concrete and only for direct probing method. For concrete with more than M – 20, we recommend to grade the quality of concrete using the parameters mentioned the table above.

NDT Result Interpretation

I.

Compressive concrete strength	Core Samples	Strength
	Raft	16 to 43 N/Sqmm.
	Remaining wall	11 to 38 N/Sqmm.
	Conical slab	from 18 to 23 N/Sqmm.
	Collapsed Silo Wall	from 11 to 30 N/Sqmm.

II.

Compressive Concrete Strength permissible value (85% of Design Strength)	Core Samples	No of results Below 25.50 N/Sqmm (85 % of M – 30)	No of results Below 21.25 N/Sqmm (85 % of M – 25)
	Raft	29%	14%
	Remaining wall	42%	12%
	Conical slab	100%	40%
	Collapsed Silo Wall	63%	38%

Note: at some locations, the present strength of site concrete was lower than the required.

III.

Compressive strength using Rebound Hammer & Ultrasonic Pulse Velocity Tests (Correlating core velocity and core strength)	Core Samples	Concrete Strength
	Raft	18 -30 N/ Sqmm.
	Remaining wall	20 -34 N/ Sqmm.
	Conical slab	10-30 N/ Sqmm.
	Collapsed Silo Wall	19 - 29 N/ Sqmm.

Note: Results indicated that at some locations the strength was observed to be less than M – 30 (Design grade of concrete) and even less than M – 25 (Site casted grade of concrete)

IV.

Depth of carbonation	Core Samples	Depth(Millimeter)
	Raft	00-04 mm.
	Remaining wall	00-10 mm.
	Conical slab	00-12 mm.
	Collapsed Silo Wall	00-05 mm.

V.

Clear Cover to main reinforcement	Particulars	Thickness
	Columns	40-70 mm.
	Beams	20-30 mm.
	Silo Wall	75-100 mm.
	Silo Raft & Conical slab	40-70 mm.
	Silo Conical slab	25-50 mm.

Note: Results indicate that a passive layer of alkaline concrete in cover zone discount the possibility of corrosion due to carbonation.

- VI. The Chloride & Sulphate contents in many of the site concrete samples were found to be more than the permissible limits. The possible source of high amount of Chloride and Sulphate could be fine aggregate (possibly dredged from creek) or construction water, which probably contained high chlorides & sulphates.

Additional Observations

- I. The design grade of Concrete is M-30 however the mix proportion of concrete raw materials used at site was 1 : 1.5 : 3 which is expected to give a strength of about 25 N/Sqmm.
- II. The site test report book reported the strength of concrete varying between 21 to 30 N/Sqmm.
- III. Water moisture / water absorption in fine & coarse aggregate was not calculated or measured every day. The corrections were probably applied on ad hoc basis to match the slump.
- IV. Concrete was prepared by volume batching and mixed in 1 bag mixer.
- V. The target slump of concrete was 45 mm.
- VI. The Silo wall was concreted using Slip Form Shuttering.
- VII. During concreting of the Silo wall, at 3 occasions the concreting was stopped for a longer time (more than permissible final setting time of cement) causing cold joints at multiple locations (17.4 m, 27 & 45 m Levels.).
- VIII. The cold joints caused by the interruptions in concreting were treated only with cement paste.
- IX. The grade of steel reportedly used was Fe-460.
- X. Steel bars were tested during construction. The submitted test reports indicated that the steel bars had passed the required 0.2 % proof stress, ultimate tensile strength, % elongation and Bend tests.

- XI. One bar of 16 mm and 20 mm dia. each, extracted from the collapsed silo wall was also tested. These test results also indicate that, the steel bars had passed the required 0.2 % proof stress, Ultimate tensile strength, % Elongation and Bend tests.
- XII. The full capacity of Silo was 22410 Tons and till date the silo was filled for a maximum capacity of @ 18000 Tons. It is reported that the Silo was filled with @ 19582 Tons material at the time of failure.
- XIII. The Plumb measurement of the remaining portion of Blending Silo wall were, North = + 5 mm, West = + 5 mm, South & East = + 8mm (+ at top of wall w.r.t bottom). The diameter of the entire silo had increased at 17.0 m level by about 5 to 8 mm.
- XIV. There was neither a settlement of the soil nor any tilt in silo wall during construction. The Silo had also not shifted in plumb even after impact of collapse.
- XV. The entire RCC design was re-checked using FEM analysis & findings were as below –
- The entire design was checked as per Indian Standards, as the earlier design consultant had followed IS codes including that for wind and earthquake forces.
 - The entire design is checked for two cases,
 - Case 1 – Concrete design strength as M – 30 and Steel of Fe – 415 grade, as assumed in original design calculations.
 - Case 2– Average Concrete strength of core samples for different components,
- | | |
|--------------|----------|
| Raft | M-20 |
| Conical Slab | M-17 |
| Steel Grade | Fe - 415 |
- The Vertical pressure in original consultant's design showed 24.732 T/m². However as per angle of repose it works out to be 34.62 T/m². This had an effect on inverted conical slab and other related structural member designs.
 - Raft:
 - The required reinforcement was more than the provided reinforcement on both sides & both directions.
 - Theoretical Crack width was more than the permissible limits along both sides & both directions.
 - Wall:
 - For Silo wall below EL (+) 17560, the required reinforcement was more than the provided reinforcement along both sides & both directions.
 - Direct compressive stress at a level where thickness of wall changes was checked and it was about 9% greater than that permissible for M – 30 grade ($0.25 \times 30 = 7.5 \text{ N/mm}^2$) and greater by 64 % for M – 20 grade cement ($0.25 \times 20 = 5 \text{ N/mm}^2$)
 - Wall sections above 17.5 M level were checked for M30 grade of concrete to decide the steel percentage. The Inner face vertical steel was found to be insufficient.

- iv. For wall section above 17.56 m level , the horizontal steel on both faces and vertical steel on outer face was found to be higher than the required. However, the RCC sections for this steel was found to be over-reinforced.
 - v. Due to reduction in lever arm i.e. higher cover value of @ 100 mm, the required steel in wall above 17.5 m level was more than what was provided.
 - vi. It has been noticed that, if cover is assumed as per drawings, then, the wall sections were observed to be over-reinforced (Such over-reinforced sections are not permitted in Limit State design). The failure of such over-reinforced section is brittle and does not give sufficient warning before collapse.
 - f. **Inverted Cone:**
 - i. The required reinforcement was more than the provided reinforcement and theoretical crack width was also more than the permissible limits along bottom face.
 - g. **Ring Beam:**
 - i. Was found to be within the design limits.
- **Some comments on Silo technology of using Inverted Cones and Standards to be used:**
 - a) Inverted cone silos are not immune to material blockages in the silo.
 - b) Loads that result from the discharge of cement and other similar bulk products from inverted cone silos have not been well understood in the past and this has resulted in partial or catastrophic failures.
 - c) The geometry of the inverted cone silo guarantees eccentric discharge which imposes highly asymmetric loads on the silo wall during silo operation.
 - d) Many of the cement companies have noticed that inverted cone silos are exhibiting severe structural distresses.
 - e) Revised Eurocode 1991-4-2005, has radically changed the assessment of loads on silo walls with eccentric discharge.
 - f) Various researchers have made several observations like, Aurecon Group has done the full investigation on this matter and they have concluded that wall hoop direction moments and shear forces derived by AS 3774 were only around one-third of that predicted by Eurocode. MacKay and Durac concluded that wall reinforcement normally provided for such silos was seriously deficient to resist both wall moment and shear. (Ref: MaKay, H and DURAC, J (2006) implications of new Eurocode EN1991-4 on the Design of Cement and Raw Meal Storage Silos, Cemtech Conference, Rome.)

Conclusion

1. There was some ambiguity in the Grade of concrete used at site and the actual strength of site concrete.
2. Degree of quality control during concreting was *Fair* (Ref – SP – 23 published by Indian Standards – table 40).
3. Quality & strength of steel bars seemed acceptable.
4. The Silo wall below 17.56 m level was found to be not safe in design.
5. The Inverted cone slab was found to be not safe in design.
6. The theoretical crack width in both the silo and invested cone slab was found to be exceeding the permissible value of 0.2 mm.
7. The wall thickness of 475 mm was not sufficient for compressive stress check for M-30. The actual compressive stress was exceeding by 215 % than the permissible stress assuming the site used M-20 material. And probably the silo had failed in buckling.
8. The vertical steel on inner face for the silo wall above 17.56 m level was insufficient for both M-30 and M-20 grade of concrete. The extra cover provided at site (100 mm) was also demanding additional vertical steel on inner face.
9. The RCC sections of wall above 17.5 m level (except for vertical inner steel) were susceptible for brittle failure, as they were over-reinforced.
10. According to ND test results, the silo wall which collapsed had a wide variation in the compressive strength and probably there were some locations where the compressive strength was lower than 20 N/Sqmm and may be some localized patches with strength even less than 15 N/Sqmm.
11. One of the cold joints caused by interruptions in concreting was at 27 m level, close to the location of the horizontal crack which was developed on the day of collapse and which got expanded at the time of failure.
12. Excessive amounts of water-soluble sulphate can cause expansion and disruption of concrete.
13. Study of the Design indicated that,
 - a. Wall thickness of 475 mm was not sufficient for compressive stress check for 30 N/Sqmm. The actual compressive stress exceeded by 215 % than the permissible stress. Probably the silo failed in buckling.
 - b. The RCC sections of wall above 17.5 m level (except for vertical inner steel) were susceptible for brittle failure, as they are over-reinforced.
14. The pressure calculation formula given in Indian Standard is only for silos with central Hopper bottom and may not be valid for the silos with inverted cone slab. Present Indian Standard could possibly reconsider the estimation methods for horizontal pressure on walls, especially in case of silos with inverted cone slab.

Onsite Images



Wall Collapse at about 19.5 to 20.0 m level



Major Wall portion Collapsed on North side



Excessive Cover to the reinforcement at 75 to 100 mm



Bars not yielded



***Vertical & Horizontal Crack / split at 30 m to 38 m Level. with a Bulge.
Oozing of material Spalling of cover concrete was also observed.***



05 Sec before collapse Oozing stopped - 1.00 Sec before collapse Crack widened- 0.25 Sec. On the verge to Collapse