A Forensic View to Structures' Failure Analysis

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ABSTRACT : *The study of the structures' failure is very much essential. Apart from judicial or professional necessity, the failure case study is also essential in learning lessons. With the advancement of theories and technologies in various interdisciplinary branches of science, it is now possible to know the root cause of failures of various structures. Forensic Engineering is amongst the examples of such interdisciplinary science. A systematic study and interdisciplinary research is carried out in this paper, in structure failure analysis in view of forensic science. According to National Crime Record Bureau (NCRB) many amongst cases are reported of structure failures and hence, the cases are tackled by chemical analysis of various building materials like Cement, Mortar, Concrete, Steel, etc. The systematic procedure of chemical analysis for these building materials is carried out and report is finally submitted to the court. In this paper, the significance of chemical analysis for Cement and its various mix products (i.e. concrete, mortar, etc.) is discussed in advocating the reasons of the failure.*

Keywords - Forensic Engineering, Failure Investigation, Structure Failures, Chemical Analysis, Concrete

I. INTRODUCTION

Structural failures and their investigation has become an active field of professional practice in which experts are retained to investigate the causes of failures, as well as to provide technical assistance to know the root cause. The parties involved in the litigation of the resulting claims. Since nearly all structural deficiencies and failures create claims of damages, disputes and legal entanglements, Forensic Engineers operate in an adversarial hence, in addition to their technical expertise; Forensic Engineers must have at least some knowledge with the relevant legal processes and need to know how to work effectively with claiming parties and judiciary [1].

II. TYPES OF STRUCTURE FAILURES

Failure need not always mean that a structure collapses. It can make a structure deficient or dysfunctional in usage. It may even cause secondary adverse effects [2].

Safety failure: Injury, death, or even risk to people:

- Collapse of formwork during concrete placement
- Punching shear failure in flat slab concrete floor
- Trench collapse
- Slip and fall on wet floor

Functional failure: Compromise of intended usage:

- Excessive vibration of floor
- Roof leaks
- Inadequate air conditioning
- Poor acoustics

Ancillary failure: Adverse affect on schedules, cost, or use:

- Delayed construction
- Unexpected foundation problems
- Unavailability of materials
- Strikes, natural disasters, etc

III. CAUSES OF STRUCTURE FAILURES

Structural failure does not have to be a "catastrophic collapse"; it may be a "non conformity with design expectations" or a "deficient performance". Collapse is usually attributed to inadequate strength and/or stability, while deficient performance or so-called serviceability problems, and is usually the result of abnormal deterioration, excessive deformation, and signs of distress. In short, failure may be characterized as the unacceptable difference between intended and actual performance. What can grow in the design-construction process and in the use of a structure that may result in immediate or event failure? A lot! [1]

Negligence: Failure to properly analyze or detail the design, or disregard codes and standards

Incompetence: Failure to understand engineering principles or respect the technical limitations of materials or systems

Ignorance, Oversight: Failure to follow design documents and safe construction practices

Greed: Short cuts; intentional disregard of industry requirements and safe practices

Disorganization: Failure to establish a clear organization and define roles and responsibilities of parties

Miscommunication: Failure to establish and maintain lines of communication between parties

Misuse, Abuse, Neglect: Using the facility for purposes beyond its intended or foregoing preventive maintenance

IV. WHY FORENSIC ENGINEERING?

When so ever structure fails, there comes what the reason behind it, so investigator finds out why it failed. Apart from the legal and professional necessity to determine the cause of failure, there is also, the need to learn from it lessons from it that would enable subsequent designers and builders or fabricators to avoid the pitfalls of the failed structure and develop safer alternatives. This should not result into mass disaster [3].

A. Failure Investigation and Design Process

Fundamentally, structural design requires “an ability to create a cost-efficient load-bearing scheme in accordance with a set of ‘rules’ prescribed by building codes, for minimal design cost” [4]. The design process generally commences with the designer considering a range of design concepts. Then, by using simplifying performance assumptions and an iterative process, the designer produces a single design from what may be many viable alternatives-that balances various competing factors such as physical constraints, cost, and adequate performance.

Design is, therefore, a process of synthesis, which utilizes assumptions relating to probable loads, structural behavior, and the capacity of material properties [4]. These assumptions are conservative and have been codified over the years to produce efficient and generally safe structures. To design structures by attempting to precisely predict the loads they will carry, how they will behave, and their material properties would be hopelessly inefficient and time consuming. Further, actually attempting to predict these factors to a high level of accuracy is of questionable value in the design process, given the unknowns surrounding the structure’s construction and the loads it will carry. Therefore, a key element in the design process is the management of these unknowns, rather than their investigation.

The role of this process in the design of new structures is self evident, but the process also has a number of important roles to play in the overall response to structural failure. For example, in noncatastrophic failures, an engineering design solution may be required to rectify the failure and restore the structure to its originally intended performance, regardless of whether legal proceedings arise. Likewise, in legal disputes, the satisfactory settlement of a dispute may depend on the details of a design engineer’s solution to resolve the issue, or, when causation has been determined, expert testimony may be required to ascertain whether the engineer that originally designed the structure did so with the degree of reasonable skill and care expected of a practicing engineer, a role for which engineers that typically utilize the design process are excellently placed because of their knowledge of standards and professional engineering practice.

Because of these attributes, an engineer that typically utilizes the design process also appears the ideal candidate to determine the cause of failure. However, an examination of a number of the key aspects of the design process illustrates the reason difficulties exist despite the fact that the engineer may have design experience relevant to the structure under consideration.

1) Design process objective

The objective of the design process is to identify and develop engineering solutions, not to determine causation. Although it is not suggested that design engineers approach the identification of causation with a view to developing solutions, many are simply unfamiliar with the forensic process, and, consequently, may find themselves falling back-generally unaware of the transition-on the process that they typically utilize in their role as designers. It is, therefore, not surprising that engineers can gravitate toward providing solutions to rectify the failure, or rely on determining the cause of failure in the form of "I wouldn't have designed the structure in this manner, so this must be related to the cause of failure."

2) Simplifying performance assumptions and evidence

The design process creates an appropriate design solution through the application of simplifying assumptions, and, where appropriate, errs on the side of conservatism. In new or remedial design, this is one of the design process's chief strengths, but in failure investigation, it is a critical weakness. In failure investigation, the investigator must determine the actual loads, actual structural behavior, and actual material properties at the time of failure, rather than relying on simplifying performance assumptions. This issue can be further exacerbated by the sometimes-significant differences between simplifying performance assumptions and the performance of structures in practice. Therefore, the accurate determination of the cause of failure depends on verifiable evidence (e.g., a bolt's failure surface or the cracking patterns in concrete members), and while the collection and analysis of verifiable evidence is central to failure investigation, it is not an integral part of the design process.

These limitations affect how an engineer that typically utilizes the design process approaches causation investigations. Although determining causation is a critical objective, the implicit nature of the design process can naturally move the focus of the investigation to solution development. Likewise, the engineer may fail to adequately collect and interpret physical evidence and instead rely on simplifying assumptions. These factors typically combine to frustrate the investigating engineer and increase the probability that the failure's cause may be identified incorrectly, potentially leading to repeat failures, inappropriate rehabilitation strategies, legal challenges, and/or skewed dispute outcomes.

B. Forensic Process

The key to determining structural causation is the application of the forensic process, which aims to objectively identify the technical cause or causes of failure by using available evidence. Essentially, it is the application of the scientific method to failure investigation. Noon (2000) [5], in his text Forensic Engineering Investigation, states that "a forensic engineer relies mostly upon the actual physical evidence found at the scene, verifiable facts related to the matter, and well-proven scientific principles. The forensic engineer then applies accepted scientific methodologies and principles to interpret the physical evidence and facts."

The forensic process of collecting evidence, developing failure hypotheses, testing each hypothesis against the collected evidence, and determining the most likely cause of failure, is a process of analysis, rather than synthesis. The application of the forensic process is described by Noon (2000) [5]: "First, careful and detailed observations are made. Then, based upon the observations, a working hypothesis is formulated to explain the observations. Experiments or additional observations are then made to test the predictive ability of the working hypothesis." Noon (2000) [5] then goes on to say that, "as more observations are collected and studied, it may be necessary to modify, amplify, or even discard the original hypothesis in favor of a new one that can account for all the observations and data. Unless the data or observations are proven to be inaccurate, a hypothesis is not considered valid unless it accounts for all the relevant observations and data."

This process avoids many of the pitfalls of applying a design process alone. The objective of the process is to identify the cause of failure, and the process is driven by ruling in or out a failure hypothesis based on specific evidence and generally accepted engineering principles, rather than simplifying assumptions. In other words, the forensic process relies on understanding how the structure actually behaved, rather than predicting how the structure would have behaved based on the design process. Finally, the separation of evidence collection from the development of hypotheses, in conjunction with the rigorous testing of each hypothesis against the evidence, assists the investigator to conduct the investigation in a forensically sound manner, ensuring it will not only stand up to the scrutiny of engineering peers, but also, if necessary, to the exacting demands of the legal system.

V. CHEMICAL ANALYSIS

A. General

The analysis and estimation of different types of samples collected from the site of the failure; in forensic science laboratories requires high degree of skill and expertise. The forensic scientists are following various methods for the chemical analysis of these substances in the laboratories. In this chapter, the chemical analysis methodology for cement, mortar and concrete is discussed in detail [6].

B. Sampling

1) Cement

When the sample is drawn from a cement bag, the details printed on the bag and another marking thereon should be carefully noted and incorporated in the forwarding letter. 1 kg sample of cement should be sent in an airtight plastic jar if available or it should be securely packed in polythene bag and then in brown paper to avoid exposure to moisture. Sampling is done as per the procedure as laid down in the Indian Standard Procedures of random sampling.

Sampling of Small Quantities *(Less than 12 bags or packages):* When number of bags or other packages containing the cement bears the same label on all the packages and are appearing to be similar, in such cases about 1kg sample of cement (in an air tight plastic jar) shall be drawn from each bag and sent for analysis.

Sampling of large Quantities *(More than 12 bags or packages):* When number of bags containing the cement bear the same labels on the packages and are appearing to be similar, in such cases the grouping must be done. Each group should contain about equal no. of bags and 20 percent of sample weighing 1 kg (in an airtight plastic jar) from each group shall be drawn into airtight plastic jar and sent for analysis.

2) Mortar

1-2 Kg of mortar sample accompanied by 1 kg each of cement and / or lime and sand if available from the field shall be sent for analysis. Every article should be independently packed.

3) Concrete

Concrete lumps, about 3-5 kg accompanied by 1 kg each of cement, sand and aggregate if available from the field shall be sent for analysis. Every article should be independently packed.

C. Methods of Analysis

1) Cement

a) Thymolphthalein Test (Thymolphthalein Indicator 0.1 % in ethyl alcohol)

Take 100-150 mg of cement sample in a test tube, add 1-2 ml water and 2 drops of indicator, development of blue color indicates the presence of cement, No color indicates that the sample is stone powder.

b) Heating Test

Take 0.5 gm of sample, heat it for about 20 minutes on a steel plate.

Change in color:	adulterated cement
No change in color:	unadulterated cement

c) Performance Test

Make thick slurry of cement with about 1 part of cement with one part of water and put in an empty matchbox. The cement gets hardened. The performance is tested after 24 hours just by removing matchbox and checking approx. strength of the cement by fingers, if the block breaks easily, the setting property is said to be poor. If the block does not break by fingers, the performance is said to be good.

d) Acid insoluble

Take 0.5-1.0 gm cement in a 100 ml beaker add 20 ml water to make a paste followed by 5 ml conc. hydrochloric acid, add 20 ml water, stir, digest on water bath for five minutes, no lumps should be formed. Digest further for another 10 minutes, filter through ashless filter paper till chloride free. Residue dried in oven and further incinerated in furnace at 800°C-900°C for 1 hour weigh the residue, till constant weight. Calculate percent acid insoluble.

e) Silica

Concentrate filtrate on hot plate to dryness, further dry completely without charring, then add 20 ml 1:1 Hydrochloric acid and digest on water bath for 10 minutes stir well, and filter on ashless filter paper till chloride free. Dry the residue (Precipitated silica) in oven for 1hr and then incinerate in furnace at 800°C-900°C for 1hr.weigh the residue, till constant weight. Weight of silica obtained is noted. (20 % Silica = 100 % cement).

f) Combined Ferric Oxide and Alumina

Concentrate the filtrate to about 200-ml by boiling then add 2-3 drops of nitric acid to oxidize any ferrous iron to ferric condition. Add 1-2 grams of ammonium chloride, stir, and then treat the filtrate with conc. ammonia solution till smell of ammonia persists then boil the solution containing the ppts. of Fe and Al hydroxides for few minute. Filter and wash the ppt. with hot water. Dry the ppt. in oven and ignite in platinum crucible till constant weight at 1050°C to 1100°C. Weigh as alumina and ferric oxide.

g) Determination of `Calcium` by EDTA Titration (By Patton Reeder`s indicator)

Take filtrate from ferric oxide and alumina determination in 250 ml Vol. flask adjust Vol. to 250 ml. Take out 25ml soln. in titration flask add 50 ml water, 5ml (1:1) glycerol with constant stirring then add 5ml diethylamine, further add 5-6 pellets of NaOH (pH should be more than 12) shake well, further add 50 mg of Patton Reeder`s indicator, shake well and titrate against 0.01M EDTA solution color change violet to blue.

1ml 0.01 M EDTA = 0.5608 mg of CaO.

(60 % CaO = 100 % Cement) and CaO % = 3 Silica %

Patton Reeder`s Indicator: Grind 10 mg of the indicator with 10 gm of sodium sulphate (A.R.) and store in an airtight bottle.

h) Direct Cement % by acid titration

Take 0.5 gm cement in a conical flask add 50ml of 0.5 N HCl, digest on water bath for 30 minutes, add 50 ml water and titrate against 0.5 N NaOH using phenolphthalein as an indicator. Also, perform a blank titration. Color change is colorless to pink.

Cement % = 28 × N × Diff. in reading / 3

Where, N= Normality of NaOH

2) Mortar

Mortar is the blend of cement and sand in various proportions used for various purposes. The mortar used for brickwork in house walls is generally 1:4 in proportions. For testing of mortar and brick good piece of mortar, adhering to brick from debris should be collected.

a) Testing of Mortar

Heat good piece of mortar approximately 200 gms is heated in oven at 110°C for 15 min. cool and then weigh. Separate the cement portion from sand by slowly grinding the lump in iron mortar. (To separate sand from cement lumps) Sieve the material and make three fractions as powder, fine sand and coarse sand. Weigh individually and record. Take about 5-10 gm of each fraction in beaker, add 5-10 ml 3.3 N HCl till all the material is wet with HCl, if required add further 5-10 ml HCl, to dissolve the material. The cement portion gets dissolved and sand portion is separated from cement, digest on water bath for 10 minutes & filter the liquid through filter paper, wash with water till chloride free. The filtrate is evaporated and silica determined as in earlier part, from silica cement portion in each fraction is determined, from total weight, weight of sand obtained by subtracting wt. Of cement and hence the ratio of cement to sand is calculated. Also % of cement in the sample is calculated.

b) EDTA Titrations

For filtrate same as cement normally the ratio of cement: sand used in plastering work is 1:4 (The ratio used for compound walls and such other work is 1:6 to 1:8).

3) Concrete

Concrete is a blend of cement, sand and aggregate in different proportions used for different purposes. Normally samples from debris selected are pieces of beams and slabs taken for analysis. About ½ kg sample is required for analysis dry the piece from slab/beam in oven at 110°C for 15 minutes, cool and weigh. Then grind the sample so that cement particle gets separated from sand and aggregate. Sieve the bulk with different mesh size sieves, to separate powder, fine sand, coarse sand and aggregate. Weigh the fractions so separated individually. Take about 5-6 gm from powder fraction and fine sand fraction, about 50-60 gm from coarse sand and about 100-150 gms of aggregate fraction for actual silica and calcium oxide determination. Take all the four fractions as above in 250 ml beakers; add sufficient quantity of 3.3 N HCl to dissolve the adhering cement particles. Then digest on water bath for 10-15 minutes and filter. The filtrate so obtained is used for silica determination.

a) Silica

Filtrate evaporates the filtrate to dryness on hot plate, dry silica remains in the beaker along with calcium and aluminium salts. Then add 3.3 N HCl and digest on water bath for 5 minutes. Filter the silica through ashless filter paper; wash with water until chloride free. Dry the silica in oven and further in furnace at 800°C-1000°C for 2 hours, Wash the silica so obtained. From silica calculate the weight of cement obtained in different fractions (20 % silica = 100 % cement). Each fraction contains some cement portion and rest being fine sand, sand and aggregate respectively. Take sand and fine sand fractions together. Thus calculate the total cement, total sand and total aggregates present in the sample, and hence calculate the ratio of cement: sand: aggregate also calculate the cement percentage. From filtrate of silica, calculate CaO % as detailed in cement, from CaO % also calculate the % cement in each fraction, and hence get the ratio of cement: sand: aggregate, and also % of cement in the sample. Compare the results obtained by silica and CaO.

4) Alternative Method

Keep the sample in the oven for 15 minutes and then keep them in desiccators for cooling. Weigh 10 gms of sample. Add distilled water and shake well. Add 20 % HCl and boil the solution. Distilled water and dilute HCl (i.e., 20 %) should be added up to 15ml, if required. Add a few drops of conc. HCl, warm-water/distilled water over the dissolved residue so that complete CaO dissolves in the filtrate. Make the solution up to 500 ml after adding distilled water in the flask. Transfer the solution after shaking well in the beaker. Pipette out 10ml of the solution each in 3 beakers in separately. Add 10-15 ml dilute nitric acid (20 %) in each beaker. Add 20ml distilled water in each and boil, add ammonium chloride (nearly 1 ½ - 2 tea spoon) and boil, cool the solution and then add ammonium hydroxide and boil the solution for the precipitation to be formed in the IIIrd group. Remove the beaker and allow precipitates to settle down. Filter the solution, make saturated solution of ammonium oxalate in a beaker and distilled water nearly 300 ml of solution is formed. Nearly 100 ml each of ammonium oxalate solution are added in each beaker after filtering the precipitates. Precipitates as of interfering radical are being removed in the IIIrd group. After adding ammonium oxalate solution, boil the solution for the precipitates to be formed of CaO. Filter CaO precipitate.

NOTE: Three separate solutions in beaker are taken as mean of the titration reading is taken as single reading gives error. Now, wash the precipitates with warm water till it is fee from oxalate. Take few drops of filtrate in a test tube, and $CaCl_2$ solution few drops; if precipitate forms then solution is not free from Oxalate. Wash till the residue is free from Oxalate. Keeping the filter paper carrying the precipitate in the beaker, wash the filter paper with distilled water so that, complete precipitates are transferred in a beaker. Add dilute sulphuric acid as CaO is soluble in dilute sulphuric acid. Add few drops of concentrated sulphuric acid if precipitates are not dissolved in dilute sulphuric acid completely, warm the solution. Put N/10 $KMnO_4$ in a burette and titrate it against warm solution at nearly 50-60°C i.e., till pink color appears. No the initial and final reading and mean amount of $KMnO_4$ used.

% Calcium Oxide (CaO) = Mean × 1.4

% Cement = CaO % × (100/62)

Assume the pure Cement CaO % = 62

a) Insoluble Residues

Transfer the residue of the previous test in a beaker. Add 30 ml hot water and 30 ml 2N Na_2CO_3 solution. Heat the solution below boiling point for 10 minutes. Filter it, wash the residue on the filter paper with dil. HCl (1:9) and finally with hot water till the residue is free from chlorides. Ignite the residue in a tarred crucible at 900-1000°C, cool in a desiccators and weigh.

b) Check for Chlorides

Take few drops of filtrate and add 2-3 drops of $AgNO_3$ solution, white precipitates formed indicates the presence of Chlorides, wash the residue with hot water till it is free from chlorides.

VI. RESULTS AND DISCUSSIONS

The initial tests like Thymolphthalein test, Heat test, and Performance test along with percentage of acid insoluble, calcium oxide and silica data can allow one to frame a report regarding the cement percentage with acid insoluble and cement with non-cementitious material. If stone powder is used for adulteration the acid insoluble amount for adulteration percentage but if lime or other material is used for adulteration then acid insoluble will be less and calcium oxide will be more, the correct cement percentage can be assayed from silica content. The relative standard deviations of 0.44 % and recovery of 99 % was obtained for EDTA titration. The relative standard deviations of 0.88 and recovery of 94 % was obtained for silica determination. Hence the results of the analysis of cement by the above methods are quite accurate and reproducible.

VII. CONCLUSION

Finding the root cause/reason of the failure of a structure requires loyal and delicate experienced personnel in Structural Engineering as well as in Forensic Engineering. By performing the chemical analysis of the samples collected from the scene of the failure of the structure, one can easily advocate the fact behind the failure precisely.

The study was successively carried out and conclusively we can say that, cement is complex mixture and testing of cement is a difficult task. In Forensic Context one has to certify whether the sample is cement or not, and if so, the percentage of cement in the sample. In case of Mortar and Concrete the ratio of Cement: Sand and Cement: Sand: Aggregate is very important, hence selection of the sample plays an important role. Finally, the cement content determined by above method compared with the specifications laid by the relevant codes may form the basis for reason behind the failure.

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