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Forensic Engineering Investigation into Decay of Cinder Aggregate Masonry Units

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Abstract

Cinder aggregate concrete masonry units had been in use from the late 1890's, but it was not until after World War II with the housing boom that came after peace, that cinder aggregate masonry units (cinder blocks) became the material of choice for inexpensive foundation walls as well as for party and fire walls. In the mid 1970's the inherent problems with decay of cinder aggregate units became apparent, and the product was generally removed from the market; however, hundreds of thousands of foundations built using this material are still in use and are continuing to fail. This paper discusses the cause of the failure, an acceptable method of repair, and presentation of the forensic evidence of failure due to decay in the courts.

Keywords

Forensic Engineering, Cinder Aggregate, Pop-outs, Internal Fracturing, Hidden Decay, Blast furnace slag, Unfired coal, Iron inclusions, Catastrophic collapse

History of Cinder Aggregate Concrete Masonry Units

Concrete masonry units (C.M.U.) are formed units made of concrete typically sized as 8" wide by 8" high by 16" long, or 12" wide by 8" high by 16" long, although many other sizes and shapes are available. They are usually used to construct concrete masonry unit curtain walls and bearing walls both above and below grade (foundation walls). C.M.U.'s are made of four constituent ingredients; Portland Cement, a course aggregate, a fine aggregate (usually sand), and a carefully controlled amount of water (water/cement ratio). Course aggregate is usually one of four materials: originally, pea gravel stone up to ¼ inch in diameter was used. Blast furnace slag was used from the late 1890's - this material is left over from the making of steel. It became very popular for use in concrete after World War II in the late 1940's because blast furnace slag was cheap. It was free. It recycled a waste product; something we try to do as much as possible today. Natural pumice, pulverized volcanic rock which was popularly used on volcanic islands like Hawaii, and finally heat expanded aggregates from expanded clay, shale, slate, diatomaceous slate, tuff, scoria and diatomite were also developed and used, now known by various trade names such as Waylite, Pearlite, and Vermiculite. These products came into favor in the 1970's because these materials are stable. Cinder aggregate was essentially slowly phased out. The reason for this, as originally discovered by the British Department of Scientific and Industrial Research, Royal Academy of Engineers in 1928, was that the blast furnace slag (breeze and clinker aggregate as they refer to cinders) deteriorates over time. The introduction in their report states:

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> *"In a previous publication a general account of breeze and clinker aggregates was given, but the available information was then not sufficient to allow any very definite conclusions to be drawn concerning the cause of failures of concretes made with such aggregates. The present Paper records the results of an investigation of these aggregates. In the course of the work failures have been studied that have resulted from the use of breeze and clinker in poured concrete, as well as in precast blocks and partition slabs, and pressed bricks.*
>
> *In the building industry the term 'clinker' is employed to cover well-burnt furnace residues which have been fused into lumps of varying size; the term 'breeze' is widely employed to cover any type of furnace residue varying from disintegrated clinker to fine, poorly sintered ashes containing a large proportion of combustible matter. The content of combustible matter in clinker may fall as low as 1-2 percent, and is never high, but in breezes it varies over a wide range. Contents of combustible matter up to 40-50 percent may occur, and values from 15-20 percent are common. The mean combustible content of over forty samples of breeze and clinker, and concretes made from them, examined in the present work is about 21 percent. Seven of these samples, consisting of large well fused material, would be termed clinker. Their average combustible content was 4.0 percent. Sixteen other samples were composed of smaller, more friable material such as is commonly called breeze, and their average combustible content was 21 percent. The remainder were samples of concrete, seven of which were actual cases of failure and several others were unsound. The average combustible content of the aggregates in these was 28 percent."*

Blast furnace slag contains not only unfired coal, but also little iron balls from the smelting process that gets into the cinder aggregate. Some of these can be as large as ½ inch in diameter. In the mid 1970's, the National Concrete Masonry Association recommended that concrete masonry unit manufacturers phase out the use of blast furnace slag for C.M.U.'s because of the potential for deterioration due to internal fracturing and pop-outs (little cone shaped craters on the surface of the concrete units). This was because the unfired coal and iron balls in the cinder aggregate will expand when subjected to moisture absorption from high humidity from the atmosphere or through contact with damp soils. The expansion of the iron balls and particles of unfired coal causes pressure to develop inside the concrete units over time causing pop-outs (surface spalling) or internal fracturing of the face shells and webs. Not only did the unfired coal and iron balls cause surface damage, but the internal structural integrity of the masonry units was negatively affected. Many cinder aggregate block masonry walls have actually collapsed due to this problem. There were extensive differences in the quality of the concrete units made by various manufacturers of cinder aggregate units. If one finds masonry units with evidence of pop-out damage, it is likely that not only will extensive further damage due to pop-outs continue to occur, but also extensive internal damage to the units is probable. As stated, in lieu of cinder aggregate, the concrete unit masonry industry started using naturally occurring minerals expanded by a heat process to form a lightweight aggregate as a substitution for cinders in C.M.U.'s.

The use of blast furnace slag for cinder aggregate is still acceptable under A.S.T.M. Standards for use in concrete products; however, under ASTM standards, the cinders must be run under a powerful magnet to remove any iron, then the cinders must be re-fired at 2000 degrees to burn all of the unfired coal to cinders. This was not the case back when cinder aggregate first became very popular in the late 1940's and early 1950's during the housing boom. This early use of cinder aggregates to make C.M.U.'s is the cause of extensive foundation wall failures today. The majority of basement foundation walls built from the 1940's into the early 1970's in the Northeast, were built using cinder aggregate C.M.U.'s with blast furnace slag, as Pittsburgh was the steel manufacturing capital of the world.

Cause of Failure

As an architect, professional engineer and general contractor, the author has seen extensive damage to cinder aggregate bearing walls, fire walls, and party and foundation walls, and has been involved in the repair or repair design of over 3,000 cinder aggregate C.M.U. walls, mostly in the states of New Jersey and Pennsylvania. Unfortunately, many of these types of walls have collapsed without notice, and the author has investigated the cause of numerous such collapses. Unlike structural steel or wood which has strong flexural qualities, as steel or wood begins to fail, the material deflects; obvious bending or sagging alerts building owners to the potential for failure and prompts investigation. On the other hand, masonry walls and foundations built of cinder aggregate masonry give little notice other than possibly slight to moderate horizontal joint cracking or inward movement (bowing) before they fail. It is well known that when concrete masonry fails, it fails catastrophically. In many cases, a careful inspection by an architect or engineer may lead to discovery of potential or existing problems before an actual collapse occurs, making a proper long-term repair possible.

In cinder aggregate masonry walls and foundations, most of the damage due to the deterioration of the masonry units is hidden. Hidden decay is most likely to develop towards the exterior of walls above and below grade. With C.M.U.'s above grade, the masonry is usually painted or stuccoed, but still subject to moisture infiltration and absorption. Below grade foundation walls are parged with cement pargetting and most times, but not all, are coated with dampproofing such as bituminous foundation coating. Dampproofing still allows some moisture migration through the wall. Very few basement foundation walls are ever actually waterproofed.

In January 1948 the Journal of the American Concrete Institute published "Study of Causes and Prevention of Staining and Pop-Outs in Cinder Concrete." In that publication, they state:

> *"There is no evidence that the presence of Fe_2O_3 or Fe_3O_4 in cinder concrete is particularly dangerous, but metallic iron or any iron compounds which are capable of decomposition in the presence of air and moisture must be considered as dangerous impurities."*

The article also states:

"Free lime may be formed in cinders by the decomposition at high temperatures of calcite (calcium carbonate), or the minerals gypsum or anhydrite (calcium sulphate), any of which may be present in some coals. At high temperatures these impurities may produce small, hard-burned particles which react quite differently from ordinary lime. These particles hydrate so slowly that it is possible for them to pass through the mixer and become embedded in a block before hydration has proceeded to an appreciable extent. When it does take place, it is accompanied by a considerable increase in volume, developing high pressures in a restricted space and often resulting in a pop-out. This pop-out is seldom accompanied by staining and is identified as Class 1."

As to iron inclusions, the paper recognizes:

"The reaction of iron with oxygen and carbon dioxide in the presence of moisture is accompanied by an expansion in volume, which in cinder concrete frequently causes a pop-out, accompanied by some staining."

In addition, the publication recognizes that:

"Gypsum may be dehydrated during combustion of the coal and subsequently re-hydrated in the concrete with an accompanying expansion in volume, producing a pop-out."

And also claims that:

"The stain came from weathering of particles of pyrite, FeS_2 in pieces of partially burned coal. Pyrite oxidizes in the presence of moisture to the sulphate, which is quite soluble. In solution it hydrolyzes, yielding ferric hydroxide, - the staining material – and sulfuric acid. The gypsum crystals, found beneath the pop-outs, apparently were formed by reaction of the acid with calcium hydroxide of the cement paste."

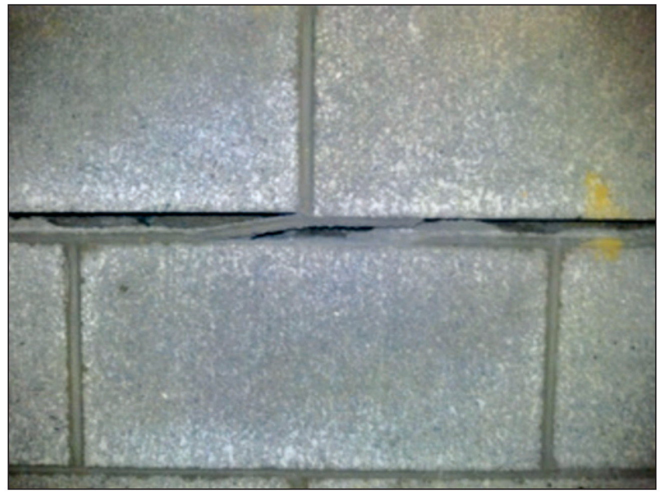
In their conclusions, the researchers stated:

"The impurities in cinders which cause staining and popping in cinder concrete have been identified. Stains are always caused by some form of iron, and pop-outs may be caused by iron, hard-burned free lime, free magnesia or by calcium sulphate."

Indications of Aggregate Deterioration

From the above, it can readily be understood that the decay of the inclusions within the cinder aggregate concrete masonry units causes an unseen gradual deterioration in the structural integrity of the units leading to a potential catastrophic collapse. In addition, as part of this deterioration, the bond between the cinder aggregate units and the mortar used to construct the wall slowly loses it adhesive qualities as the surface to the mortared- face shells deteriorates, causing the adhesive bond to decrease over time.

The author has seen this in numerous cases where an inward bowing of the masonry foundation wall occurs and the mortar can be plucked out with just two fingers from between the units – no tools necessary. The mortar has completely lost all tensile bond (See Photograph 1). The mortar tensile bond to cinder aggregate masonry units is, at best, 25 p.s.i., with a maximum of approximately 16 +/- square inches of area on the interior face shell of the unit, stressed in tension for a total of 400 pounds tensile strength to resist bending. Adding a 3/8" diameter reinforcing rod whose area is equal to 0.113 square inches, of either 60 or 80 k.s.i. steel yield strength, provides an increase in the capability of the wall to resist bending well above the original designed unreinforced strength. Adding these rods increases the tensile bond resistance to 0.6 times the yield strength of the steel used, i.e. 6.6 kips for 60 k.s.i. steel per 16 inches per wall. The majority of foundation wall failures repaired are those where long horizontal cracks in the masonry joints develop, usually one, two or three units below the exterior grade. (See Photograph 2). Typically, it has been a single longitudinal crack that becomes diagonal step crack up and down as it nears intersecting or end walls, although it is not unusual to have two or even three horizontal cracks in some cases. Usually, it is possible to repair walls with this problem if the cracks are open 3/8 inch or less. It is also possible to move the wall back to vertical by excavating the exterior backfill, then pushing or jacking the wall back into position. Once this is done, installing reinforcing in the cores and grouting as described later in this paper, restores the wall to well above its original strength.



Photograph 1
The mortar has completely lost all tensile bond strength.

Photograph 2
On this wall, two horizontal cracks developed on the wall at 3 and 5 courses below the top of the wall, i.e. the approximate center of the wall height.

Installing reinforcing in the wall in this manner does not make the wall in any way qualify as a “reinforced masonry” wall as defined by the A.C.I. or N.C.M.A. since no horizontal reinforcing is provided. Essentially, it could be considered a series of spaced concrete studs with infill panels to hold back the earth. The pea gravel grout bonds with the existing cinder aggregate concrete of the masonry units helping to re-solidify the fractured units.

Photograph 3
Pop-outs and rust stains on the surface of a masonry wall are indications of iron inclusions under the surface.

As to the procedures for determining the conditions of cinder aggregate masonry walls, the first is visual inspection of the masonry units, looking for pop-outs and rust stains on the surface, an indication of iron inclusions under the surface (See Photograph 3). Looking closely at the surface, it is also possible to detect hairline cracks on the interior face shell of the cinder aggregate masonry wall indicating the possibility of internal fracturing of the webs and exterior face shells. Sounding, by lightly tapping on the face shell with a hammer, also provides an indication of internal fracturing. Typically, if the unit is not severely fractured internally, the sound produced will be a ping or ringing sound. If the sound is more like a dull thud, it is a sure indication of internal fracturing and deterioration. The amount of wall area that is determined to be damaged by sounding is an indication of the extent of the problem. Deciding whether to either repair or replace the wall is a matter of engineering judgment based on knowledge and experience.

Acceptable Methods of Repair

The structural systems (cinder aggregate masonry units) discussed in this paper, pre-date currently used structural systems and have inherent defects in the materials. The following remediation offered has been used with substantial success and the remediation has been seen to be effective over the past twenty or more years. The finished product is not in strict conformance with any current building code. (Nor is it in conformance with the current ACI building code for reinforced masonry.) However, it does offer economies to extend the life of the building foundation for the property owner, short of complete replacement of the entire foundation. This method has been accepted by numerous local construction officials and is currently accepted by New Jersey state agencies.

Foundation walls that have horizontal cracking at the mortar joints and have a slight inward bow, ie., less than one inch bow but do not have extensive evidence of cracking, deterioration and pop-outs, can be repaired by installing #3 (3/8") reinforcing rods in the cores of the hollow masonry units at 16 or 24 inches on center, depending on the designer's judgment based on experience. In order to do this, holes are cut into the cores of the units at the top, middle, and bottom of the wall. The reinforcing can then be inserted through the center hole and fished up and down. The bottom hole is used to clean out any mortar or debris that is at the bottom of the wall and to insure that the grout is flowing freely to the bottom; however, occasionally conditions are encountered where the mason, when originally constructing the wall, used solid or semi-solid blocks mixed in with the normally hollow C.M.U.'s, likely in an effort to just use up units left over from other projects. This prevents the installation of the rods and blocks the free flow of grout. If the basement slab abuts the foundation wall, the rods are simply held in place by wires 1 ½ inches inside the interior face of the masonry unit face shell. If the basement slab abuts the footing, it is necessary to drill into the concrete footing 2 to 3 inches and then epoxy the rod in place in the footing. The rods are lapped at the center hole 8 inches and wired together and held in place 1 ½ inches inside the face of the interior face shell by wire ties. At the top of the foundation wall, three conditions can be encountered: The top unit is hollow, the top unit is a cap block, or the top unit is a solid 4" slab. The first two conditions are not a problem because a hole can easily be cut in the units and the reinforcing held in place by wire ties. As to the third condition, it is necessary to drill into the unit and epoxy the reinforcing in place, or run an anchor bolt through the mud sill plate and the 4 inch block unit tying it to the reinforcing rod. A 90 degree angled hammer drill with a ½ inch masonry/concrete bit can be used to do this.

The architect or engineer should also check to determine if the wood mud sill plate is properly anchored with anchor bolts to the masonry foundation wall. New Jersey adopted the New Jersey Uniform Construction Code and the 1975 BOCA Basic Building Code on January 1, 1976. Before that date, each township in New Jersey had its own building code, if any. Most did not require framing anchorage to the foundation. Pennsylvania did not adopt a statewide building code until 1999 and New York until 2002. If there is no anchorage, the author recommends installation of anchor bolts at 4 or 6 foot centers, depending on the height and condition of the foundation wall. The anchor bolts are wire tied to the reinforcing prior to grouting. The design professional should always inspect the installation of the reinforcing prior to grouting.

The mix used for grouting is as per the table below. An additive such as "Grout-Aid" manufactured by Sika, or a similar additive can be used to facilitate grout flow. These additives not only improve the grout flow, but also improve the strength of the grout and its bond to the damaged and deteriorated masonry, re-bonding the fractured sections together. All grout for masonry cores shall conform to ASTM-C476 and shall have the following proportions by volume for course grout as follows:

Parts by volume – Portland Cement	1
Parts by volume – Hydrated Lime	1/10
Aggregate, Sand and Pea Gravel,	1 to 2
(Measured in a damp, loose condition)	

Once the reinforcing is inspected and approved by the design professional, grouting can begin. Grouting is started at the center hole, and the bottom hole observed to insure that the grout is reaching the bottom of the wall. Once this is determined, the bottom hole is blocked and the pour continues up to the center hole. Once the grout reaches the center hole, that hole is blocked and grout is poured in the top hole. Once that is done, a stiff grout is used to fill the top hole, encapsulating the reinforcing and any anchor bolts installed. It must be noted that in many states, this work is considered a structural repair and requires a building permit with inspections by the local authorities. Obviously, this is a structural repair and a building permit should be obtained. This protects the owner when selling his building. Today's home inspectors, many of whom are architects or engineers, can detect and report on foundation walls that have been repaired. Records of permits and inspections prove the project was performed properly.

As to pushing a bowed wall back to vertical, this is not as complicated as it sounds; in

one case in which the author was involved with a 1950's three-story residence, once the soil on the outside of the foundation wall was carefully removed, the wall moved nearly back to vertical by itself just from the weight of the building pressing down on the foundation. The wall should be braced on the inside prior to excavation and not backfilled until the reinforced wall has set for at least three days. With the outside of the foundation being excavated, it is easy to re-dampproof, or at the owner's request, install actual waterproofing on the exterior of the foundation wall.

Presentation of Evidence of Decay to Insurance Companies and the Courts

Although many homeowners' insurance policies do state that the residence is covered for hidden decay, unfortunately, many insurance companies will deny any such decay claim for cinder aggregate masonry failure by attempting to claim that the term "decay" applies only to wood. Another obstacle which must be argued and overcome with the insurance company involves "exclusions for bowing and earth movement." Fortunately, the judges in some cases in which this author has been involved ruled in the homeowners' favor stating that decay is decay, no matter what caused the decay or what decayed, and that cinder aggregate masonry deterioration due to swelling of unfired coal and rusting iron balls is decay. The definitions of "decay" used by two judges in two different cases were from the Merriam-Webster Dictionary which is as follows:

"Decay –

1: to decline from a sound or prosperous condition

2: to decrease usually gradually in size, quantity, activity, or force

3: to fall into ruin

4: to decline in health, strength, or vigor

5: to undergo decomposition"

Judges have ruled that if the bowing and earth movement was a result of the hidden decay, the decay was the primary cause of failure, and that the bowing and earth movement exclusion was not applicable because it was the result of the hidden decay and not the primary cause of the foundation failure. As a forensic expert reviewing the condition of a failed or failing cinder aggregate masonry foundation or exterior bearing wall, one should consider, look for and sound for, signs of hidden decay and deterioration within the structure of the masonry units, and, with the client or their attorney, review the language of the policy to ascertain if it allows for hidden decay, which may be construed by the courts to be a legitimate claim and provide funds to cover the costs of the wall repair.

Conclusion

Although catastrophic failures may occur in foundations using cinder aggregate masonry units, it is possible for the forensic engineer or architect to investigate, detect, and propose a repair of the condition before such failures occur. Engineering judgment, based on experience, will determine if the wall should be repaired or replaced. It is also necessary to properly present such claims to insurance companies and/or the courts in a way which will allow a building owner to realize the full benefit of the “decay” provision of their insurance policy.