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Usage of Coal Fly Ash and Bottom Ash from Ash Ponds for Bricks and Precast Concrete Blocks – A Review

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Abstract

As larger amounts of coal are burned every day to produce electricity for a growing population, more coal ash is produced and stockpiled in large landfills and ash ponds. The ever-increasing stockpiles of unutilized Coal Fly Ash (CFA) and Bottom Ash (CBA) are a growing health and environmental concern. Studies have shown that communities living near ash ponds are subjected to an increased risk of respiratory illness, and the stockpiles can also potentially cause environmental pollution due to leachate. The potential utilization of CFA and CBA is to use them as natural aggregate substitutes for construction materials such as mortar, bricks and precast concrete. This paper aims to review recent studies on the usage of CFA and CBA in producing brick and precast concrete blocks, the changes in the properties of the CFA or CBA bricks and precast concrete blocks compared to control samples, as well as the effects of seawater intrusion into the concrete mix, which indicate the potential effects of using CFA and CBA stored in coastal ash ponds.

Keywords: Coal Fly Ash (CFA), Bottom Ash (CBA), natural aggregate replacement, brick precast concrete blocks, concrete properties

1. Introduction

Coal is among the most common type of fuel used to generate electricity around the world. This is due to its relatively low cost compared to other types of fuel such as natural gas and fuel oil. The combustion of coal for power generation in turn yields unwanted Coal Combustion Products (CCP), which are ash and slag. Coal ash can generally be separated into two main categories, which are Coal Fly Ash (CFA) and Coal Bottom Ash (CBA). Globally, it is estimated that around 750 million tonnes of coal ash are generated annually, and at a growing rate (Bielecka & Kulczycka, 2020). Out of the total ash produced, most of it is in the form of CFA (70-80%), and the remainder is CBA (Mohammed et al., 2021). In Korea, only 40% of CBA is reused, while the remainder is stockpiled in landfills (Kim et al., 2021).

CFA is a lightweight byproduct of coal combustion, which is usually trapped in the exhaust stack filtration system of a coal power plant. With main constituents of Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), Iron (III) Oxide (Fe_2O_3) and Calcium Oxide (CaO), it also contains some amounts of heavy metals, but the presence is dependent on the properties of the coal used for combustion (Sakir et al., 2020). Having spherical particles, it improves the flow properties of concrete as well as participates in the pozzolanic reaction, due to its SiO_2 content.

CBA is heavier and contains more heavy metals, and is deposited at the bottom of a coal power plant furnace. Studies have shown that CBA has the potential to leach heavy metals such as Copper (Cu), Lead (Pb), Zinc (Zn) and Nickel (Ni) (Sakir et al., 2020). CBA particles are generally larger, porous and more angular compared to

CFA. The particle size of the CBA is less than 300 µm and can be considered as "fine" grade aggregates while CFA is smaller in size than CFA. The larger particles observed (> 300 µm) were probably due to agglomeration of small BA particles which include slag and clinker (Zainal et al., 2020).

In a coal power plant, a common method of handling and storing CFA and CBA are through stockpiling them in large designated areas known as ash ponds. These ash ponds are specially engineered ring embankments, where the CFA and CBA are stored in landfills, either wet or dry forms. Special care is also taken to prevent the release of unwanted leachate into the groundwater of the surrounding area by having geotextile membranes or low permeability layers.

However, this practice of landfilling, coupled with the low utilization rate of CFA and CBA globally, leads to huge stockpiles of unwanted material being stored. The costs associated with maintaining such stockpiles and constructing new ash ponds to contain the ever-increasing amounts of CFA and CBA are high. Utilization of CFA and CBA is generally low globally, with utilization limited to about 68%wt in China, 47%wt in Europe, 39%wt in the US, 15%wt in Russia, 10%wt in Australia and generally 25%wt worldwide (Ranjbar & Kuenzel, 2017).

These ash ponds may also lead to hazards to human health as coal ash contains fine particulates which are detrimental to respiratory health. As an example, in 2019, a study conducted has shown there is an increase in the number of adults with respiratory illness and irritation in four communities located near Southwest Louisville, Kentucky (Hagemeyer et al., 2019). These communities were located near a coal power plant with ash storage facilities.

There is also a possibility of environmental contamination through the leaching of materials from coal ash. In leaching tests conducted on Mozambican coal and coal ash samples, one ash sample out of 6 samples tested contains high levels of As, and is easily reachable, while two other coal ash leachate samples contained high levels of Cr and Mn (Marove et al., 2020). However, the potential of leaching is heavily dependent on the on-site geochemical condition (Schwartz et al., 2018).

One promising method of utilizing CFA and CBA which are widely being studied by using them to replace natural materials used in making concrete. The potential advantages of this method of utilization are high, as the mining of natural materials such as sand and gravel for concrete making causesdamages to the environment. The usage of CCP is directly related to the United Nations Sustainable Development Goals (SDGs), where the target of SDG 12 is to “ensure sustainable consumption and production patterns” (Zhou et al., 2022).

This paper presents a review of the utilization of CFA and CBA from Coal-Fired Power Plants in the production of building materials such as bricks and precast concrete blocks.

2. Recent Studies on Bricks and Precast Blocks using CFA And CBA

Table 1 below shows the summary of several recent studies on the utilization of CFA and CBA in making bricks or precast concrete blocks. From the review of CFA and CBA utilization for bricks and precast concrete blocks, there are several observed trends of changes in the properties of the bricks and precast blocks compared to control samples.

From the review conducted, several trends were observed which are related to the usage of CFA and CBA, which are reduced workability, change in compressive strength, change in durability and density, sound absorption and thermal conductivity.

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Table 1. Summary of recent studies on CFA and CBA bricks and precast concrete blocks

Ref.	*Type of Brick/Precast Block*	*Findings*
(Rodríguez-Álvaro, González-Fonteboa, et al., 2021)	CBA Concrete Blocks and Masonry Units	• Decreased workability due to water absorption by CBA • Porosity increases leading to reduced density with increasing CBA content • Reduction in compressive strength due to weakness of CBA. • Water absorption by immersion increase
(Ashish Deepankar et al., 2018)	CFA + CFA Unfired Bricks	• Increase in compressive strength and modulus of rupture with an increase in CBA content • CBA bricks more durable than non CBA bricks
(Sutcu et al., 2019)	CFA+CBA Fired Bricks	• Reduction in porosity when bricks are fired at higher temperatures, leading to lower absorption and higher bulk density and thermal conductivity • Higher CFA content causes an increase in porosity, while dead to higher water absorption decreasing bulk density and thermal conductivity • Increase in CFA and CBA content leads to a significant decrease in compressive strength
(Debnath et al., 2022)	CFA+Ball Clay Fired Bricks	• 50% CFA and 50% ball clay mix suitable for refractory bricks – meets ASTM standard for thermal conductivity, Cold Modulus of Rupture and Cold Crushing Strength
(Abbas et al., 2017)	CFA + Clay Fired Bricks	• Lighter bricks – 18% reduction in weight with 25% replacement of clay with CFA • Compressive strength and modulus of rupture decrease with increasing CFA content • 20% CFA replacement – 11MPa compressive strength • Increasing CFA content reduces efflorescence, due to CFA binding the free lime and salts • Water absorption reduces with an increase in CFA content
(Masuka et al., 2018)	CFA, Lime, Wood, Aggregates Unfired Bricks	• Lower wet compressive strength • Higher dry compressive strength (after 28 days of curing)
(Li et al., 2021)	CFA, pebble, lime Fired Bricks	• Water permeable bricks produced which meet industry standards • Compressive strength increase with increasing forming pressure, but has the opposite effect on permeability
(Doğan-Sağlamtimur et al., 2021)	CBA + Clay Fired Bricks	• Successful substitution of clay in fired bricks with CBA up to 40%
(Dacuba et al., 2022)	CFA Fired Bricks	• No detriment to brick properties with change in unburnt carbon content • Higher CO2 emission for CFA with higher unburnt carbon

(Eliche-Quesada et al., 2018)	CFA Fired and Unfired Bricks	• Increase in CFA content decreases the bulk density, with an increase in porosity and water absorption
(Elahi et al., 2021)	CFA + earth Unfired Bricks	• Addition of CFA alone could not increase compressive strength, some cement content is needed • Addition of CFA increases the compressive, split tensile and shear strength compared to cement-earth bricks
(Turgut et al., 2021)	CFA + lime Unfired masonry units	• Potential production of masonry units without cement; using normal and hydrated CFA, lime and high range water reducer (HRWR) additive
(Gupta et al., 2021)	CFA +hydrated lime + stone dust Unfired Bricks	• Bricks can be produced with CFA, with hydrated lime as a binder • Optimal mixing sequence can improve the properties of the bricks produced
(Sritharan et al., 2021)	CBA Unfired Bricks	• Cement block containing 45% CBA as fine aggregate replacement achieves 2.94 N/mm2 compressive strength. • Water absorption at 28 days was recorded at $164 kgm^{-3}$ • Significant reduction in weight and density up to 16% • Vibro-compaction method can be used to produce bricks
(Fonseka & Nanayakkara, 2020)	CBA + foaming agent Foam Concrete Blocks	• Usage of CBA with foam agent produced lightweight concrete blocks • Compressive strength increase with the increase in CBA / Cement ratio. Maximum compressive strength was 3.8MPa at CBA/C ratio of 0.75 • CBA particles less than 2.36mm in size are best in producing foam concrete blocks • Water absorption is higher than typical concrete blocks, thus advised to be used for indoor non-loading bearing applications
(Antoni et al., 2017)	CBA+CFA Concrete Paving Blocks	• CBA can be used to completely replace sand in concrete paving blocks. • Combination of 50% CBA passing through 5mm sieve and 50% CBA passing through 10mm sieve, with 50% fly ash cement replacement, can yield blocks having 40MPa compressive strength • All samples produced can achieve good abrasion resistance. However, CFA contents reduce abrasion resistance
(Nurzal et al., 2017)	CFA Concrete Paving Blocks	• Addition of 5%wt CFA into the concrete mix increases compressive strength after 35 days of curing • Increasing compaction pressure of the press machine increases the compressive strength of the paving blocks
(Karolina et al., 2018)	CFA+CBA Concrete Paving Blocks	• Highest compressive strength was recorded for paving block with 25% CBA substitution • Water absorption increase with the increase in CFA and CBA contents

3. Effect of CFA and CBA Utilization on Brick and Precast Concrete Block Properties

3.1. Workability of Fresh Mix

Through studies conducted by various researchers, it is found that increasing CBA contents leads to a reduction of compressive strengths of the bricks or precast concrete blocks produced. This is due to the porous nature of CBA, which increases water absorption and reduces the amount of free water for the workability of the concrete mix. This may increase the difficulty of moulding concrete mixes for brick or precast concrete block making. A decrease in fluidity is also observed when CBA is used in a concrete mix, owing to its irregular shape. However, an increase in fluidity may be observed during mixing, which is attributed to the centrifugal force which draws the water from the CBA out into the concrete mix (Rodríguez-Álvaro, Seara-Paz, et al., 2021).

In another study conducted by Rodríguez-Álvaro, González-Fonteboa, et al., (2021), the suitability of CBA as a partial replacement for conventional aggregates was investigated, specifically for masonry mortars, precast concrete and masonry units. Two types of CBA were used, which were CBA1 originating from the combustion of Russian bituminous coal, and CBA2 from the combustion of Indonesian sub-bituminous coal. It is found that the workability of the mixes decreases due to the irregular shape and water absorption of the CBA, with CBA2 exhibiting more workability reduction compared to CBA1. This was attributed to the presence of fine rounded particles in the CBA1 mortar mix, however, in general, both mixes have lower workability compared to control mixes.

3.2. Effect on Compressive Strength

Through studies conducted by various researchers, it is found that CFA and CBA addition changes the compressive strengths of the bricks or precast concrete blocks produced.

CFA is widely known to be a supplementary cementitious material, which is capable of pozzolanic reactions. Studies have shown that with a low water/binder ratio, properly combining raw materials and application of heat curing at 60°C, there is a potential to replace up to 80% of cement content of concrete with comparable compressive strengths (Yu et al., 2018). The pozzolanic effects from CFA may also be influenced by the type of coal and the technology used. From studies conducted by Śliwiński et al., (2021) on fluidized bed combustion fly ashes, CFA from bituminous coal had practically no effect on the strength after 28 and 90 days curing period, while CFA from lignite coal had a significant positive effect. However, the improvements to the concrete mix from the CFA pozzolanic reaction may occur slower, as found by Saha (2018). The initial compressive strength after 28-day curing was found to be lower and decreased sharply with additional CFA content. But this early low compressive strength trend is followed by a gradual increase up to 180 days of curing.

Most of the studies conducted on producing brick or precast concrete blocks observed a reduction in compressive strength of the sample with higher amounts of CBA, which can be seen in Table 1. This trend of reducing strength is also reflected in the properties of the concrete used for bricks or precast concrete casting. In tests conducted by Ramzi Hannan et al., (2020), CBA is used as a fine aggregate replacement, with varying percentages of replacement from 0% (normal concrete) to 100% (full use of CBA as fine aggregate). 100mm cubes were cast and tested after curing for 7, 28 and 90 days. Generally, at 7 days of curing the compressive strength of CBA concrete is less than the normal concrete, with the lowest strength recorded at 100% CBA fine aggregate replacement. However, at 40%-60% CBA fine aggregate replacement, the compressive strength of the mix exceeds the control concrete mix. This trend continues up to 90 days of curing. According to Ramzi Hannan et al., (2020), the lower compressive strength may be attributed to the internal curing effect, where the water from the cement paste is transferred to the CBA, causing a delay in the hydration process. The increasing voids due to the porous nature of CBA also lead to decreasing compressive strength.

Park et al., (2021) conducted tests using concrete mixes containing varying CBA content as a fine aggregate replacement, with the addition of CFA to replace cement. Cylinders measuring 100mm diameter x 200mm lengths were used for compressive and splitting tensile strength testing; as well as 100mm x 100mm x 400mm prisms for flexural tensile strength. From the tests conducted, it is found that the compressive, splitting and flexural strengths reduced with increasing CBA content. Tests also showed the influence of curing and moisture effect on CBA concrete, where samples were tested at Saturated Surface Dry (SSD) and oven dry conditions. It is found that SSD samples had approximately 15% more compressive and splitting tensile strength compared to oven-dried samples.

Yang et al., (2020) experimented further with the possibility of replacing fine aggregates in High Strength Concrete (HSC) with compressive strengths greater than 60MPa. The CBA concrete is produced with a water-cement ratio of 0.3, and the addition of a high water-reducing agent (HWRA) to improve workability. Based on the tests conducted, HSC with compressive strengths exceeding 60MPa can be produced, even with the total replacement of fine aggregates with CBA. However, there is a reduction in compressive strength compared to the control HSC. The higher porosity of the CBA concrete due to the porous CBA aggregates is the main reason for this reduction in strength, as CBA is generally weaker than natural aggregates. But the reduction is generally less than 9% at 28 days of curing and less than 7% at 56 days of curing.

Through the studies by Rodríguez-Álvaro, González-Fonteboa, et al., (2021), it is found that CBA originating from Russian bituminous coal combustion (CBA1), at low amounts exhibited better potential as aggregate for masonry mortars, as there are less unwanted effects on workability, mechanical and durability properties. However, CBA originating from Indonesian sub-bituminous coal combustion (CBA2) was proposed as aggregate for high-performance concrete having low water to cement ratio, as some autogenous swelling was detected in masonry mortars, which indicates the potential being an internal curing water reservoir. Results from tests conducted on precast concrete and masonry units cast using CBA2 showed that high amounts of CBA contents resulted in less dense precast concrete and masonry units, which would be favourable in the construction of buildings as it results in less weight for transport and handling, and less load on structures. However, there is a significant reduction in the compressive strength of the precast concrete and masonry units compared to control samples, especially at replacement percentages exceeding 20%.

In a study on the usage of coal pond ash, which is a combination of CBA and CFA, it was found that the addition of only 10% pond ash increased the compressive strength of concrete (Yuvaraj & Ramesh, 2021). However, in this study, the percentage of CFA to CBA is not investigated, and pond ash is regarded as a uniform homogenous material.

3.3. Durability

3.3.1. Carbonation and chloride ingression resistance

Savadogo et al., (2020) studied the durability of cementitious mortar made from CBA powder from SONICHAR in Niger. Cylindrical samples of 40mm diameter and 60mm height were cast using different mixes, with varying amounts of CBA powder added to replace the binder, which was Portland Artificial Cement (CEM 1), and cured for 90 days in water saturated with lime. Through the study conducted, it is found that the partial substitution of CBA with CEM 1 increases the penetration depth of CO_2, which can potentially cause significant degradation of the mortar if the CBA substitution exceeds 10%. However, after carbonation, samples having CBA substitution had higher electrical resistivity compared to the control mortar, which is advantageous for the protection of reinforcement against corrosion. Partial substitution of CBA also causes an overall increase in porosity, which leads to an increase in degradation depth.

The inclusion of CFA and CBA into concrete also improves its resistance against chloride ingression. Studies on mortars containing coal ash of 35%wt show a reduction in chloride diffusion coefficient from 23 x 10^{-12} m^2/s to 4.5 x 10^{-12} m^2/s compared to control mortars (Menéndez et al., 2019). This property would be beneficial for precast concrete blocks containing reinforcing steel or part of a building system which is in contact with steel. This chloride ingression resistance is also observed in a study by McCarthy et al., (2020), who added that higher w/c ratios increase this effect even further.

These findings on CFA concrete resistance towards chloride ingression is also supported by Saha (2018), where tests using Class F fly ash as a partial binder replacement resulted in lower chloride permeability after curing for 28 and 180 days. These findings are related to the alkali binding and low interconnecting voids, as well as improvement in the binder matrix density.

3.3.2. Control of Alkali-Silica Reaction (ASR)

Abbas et al., (2020) explored the pozzolanic behavior of untreated CBA and its possible application to control unwanted Alkali-Silica Reaction (ASR) expansion that may occur due to the usage of aggregates containing reactive silica. In the tests conducted, varying percentages of CBA against cement mass were used. From the tests conducted, it is found that specimens containing CBA exhibited less ASR expansion compared to specimens at 14 and 28 days of curing. Specimens containing CBA also showed no microcracking and had a more dense structure when examined using SEM. As the tests also concluded that the compressive strength of the concrete was comparable at 10% CBA, it was recommended that CBA be used as cement replacement at low amounts to control ASR expansion.

3.3.3. Sound Absorption

Experiments on the sound absorption properties of concrete made using CBA were conducted by Ramzi Hannan et al. (2020). Test panels measuring 0.3m x 0.22m x 0.1m for reverberation room testing were cast using concrete mixes having varying percentages of CBA fine aggregate placement. Through the reverberation room testing, it is found that panels with 80%, 90% and 100% CBA fine aggregate replacement had good sound absorption capabilities and can be considered Class D absorbers (capable of more than 30% sound absorption).

3.3.4. Thermal Conductivity

Yang et al. (2021) investigated the thermal conductivity of concrete containing CBA under different drying conditions. In the test conducted, CBA was used as a fine aggregate replacement material at volume ratios of 25%, 50%, 75% and 100%. Cylindrical specimens measuring 100mm x 200mm were used and different curing and drying conditions were imposed. Samples representing water curing and SSD conditions were cured in water until one day before testing; while samples representing over-dried conditions were cured for 7 days in water after demolding, then air cured, and finally oven-dried in a chamber 24 hours before testing. The thermal conductivity of CBA concrete decreased 15~20% under over-dried conditions compared to SSD conditions, mainly due to the increased amount of pores without moisture in the CBA concrete. Thermal conductivity also decreased significantly with increasing CBA content. This is in line with the fact that CBA is very porous, thus is capable of trapping air or moisture at higher amounts compared to conventional aggregates. Thus, the reduced thermal conductivity due to the usage of CBA will be advantageous in reducing external heat transfer into a building, which reduces energy consumption. However, the thermal conductivity also increases with curing age. In another study by Yang & Park (2020), it is found that as the curing age is increased to 56 days, the thermal conductivity increases by 3.1-6.5%.

4. Effect of Seawater Content in CFA and CBA from Ash Ponds

Due to the need for large amounts of water for cooling and steam generation, many coal power plants are situated near large bodies of water, usually the sea. Coastal Coal Power Plants are more likely to have ash ponds located near the seaside, and the CFA and CBA landfilled in these ash ponds are exposed to the deposition of chloride ions from seawater, which can be transported by many means such as through sea breeze. There are also the ash flushing systems used in Coal Power Plants which utilize seawater as the main transport medium to carry the cash from the boiler to the ash ponds. This seawater intrusion may cause changes in the properties of the concrete used in moulding bricks and precast concrete blocks.

Table 2 summarizes the findings of several studies regarding the effects of seawater content in concrete mixes, which may be indicative of the effect of seawater content in CFA and CBA concrete mixes.

Table 2. Effect of Saltwater on Concrete Properties

Reference	*Summary of Findings*	
(Younis et al., 2018)	• Gradual gain in compressive and tensile strength until Day 7	• Reduction in workability and its retention, as well as setting time • Reduction in compressive strength from 7 days to 28 days • Slightly higher shrinkage
(Li et al., 2019)	• Slightly higher cube strength	• Reduced workability, lower density and reduced water film thickness
(Wang et al., 2020)	• Compressive strength increased initially from 1 to 7 days	• Reduction in compressive strength after 7 days
(Liu et al., 2021)	• Reduced porosity due to large amounts of chloride ions, leading to increased carbonization resistance • Increased strength	• Reduced compressive elastic modulus
(Vafaei et al., 2022)	• Finer pore size and lower porosity	• Higher autogenous shrinkage • Increase in drying shrinkage strain

5. Treatment to Reduce Hazardous Material Leaching

CBA generally requires some treatment to enhance its usability in concrete (Gooi et al., 2020). Typical physical treatments are sieving, grinding, burning and soaking. These physical treatment aims to either maximize fineness (sieving and grinding) or to remove impurities (burning and soaking). Chemical additives are also used for treatment, however physical treatments are generally more preferred worldwide for CBA research as chemical additives require more care in their application, requiring skilled labor for handling and more controlled environments for storage and processing. Studies on chemical treatment using carboxylic acids have also been successful in leaching rare earth elements from coal ash, which would make it even safer for use in construction (Banerjee et al., 2021).

Hashemi et al., (2019) have shown that stabilization with CEM1 cement, which is Portland Cement with a maximum of 5% of other materials, is suitable for reducing leaching of Cu, Cd, Ni and Pb from CBA. In a study by Gupta et al. (2017), the leaching behavior of CFA bricks is better than Clay Bricks, due to their pozzolanic nature and the encapsulation of heavy metals.

Thus, the application of CFA and CBA in bricks and precast concrete blocks would be preferred as the cement and binder contents would help prevent any release of heavy metals through leaching.

6. Gap of Knowledge

From the review conducted, the following are the gap of knowledge that may be further explored:

- The possibility of brick or precast concrete block production using a semi-dry mix of CBA and CFA concrete using high pressure and/or vibration. This method is common for cement sand bricks. Most studies on CBA and CFA bricks and blocks utilize either semi-dry moulding with some compaction then firing in a kiln or furnace, or casting of wet mixes into moulds and curing. Studies can be conducted on the optimum mix design, the appropriate moulding pressure to be applied, and the vibration times for compaction.
- The effects of high seawater contents in CBA or CFA are not well researched. Some coal power plants utilize seawater to transport the CBA or CFA to the ash ponds, which leads to high contents of chloride and other seawater constituents. As shown in Table 2, there is a marked difference in the properties of fresh concrete which contains seawater compared to freshwater. Thus, this may lead to changes in the properties of bricks or precast concrete blocks produced.
- Pretreatment methods may be explored to further enhance the properties of CBA as well as reduce the seawater content of CBA and CFA obtained from ash ponds

7. Conclusions

The utilization of CFA and CBA needs to be increased, as the ever-growing amount of CFA and CBA produced every day from electricity generation will eventually lead to problems in providing enough space for landfilling, as well as increasing the cost of maintenance for existing ash ponds. Large amounts of CCP may also lead to potential health problems as well as risks to the environment.

Thus, the utilization of CFA and CBA as substitutes for aggregates in bricks and precast concrete block production holds great potential. The utilization of these waste materials can help reduce the pressure on the environment. However, the properties of CFA and CBA will influence the fresh mixes as well as the hardened bricks or precast concrete blocks produced. Thus, attention should be given to the changes in workability, compressive strength and durability as they will influence the potential application of the bricks and precast concrete block produced.

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