Coal Ash Reuse Options: A Strategy for Moving Forward

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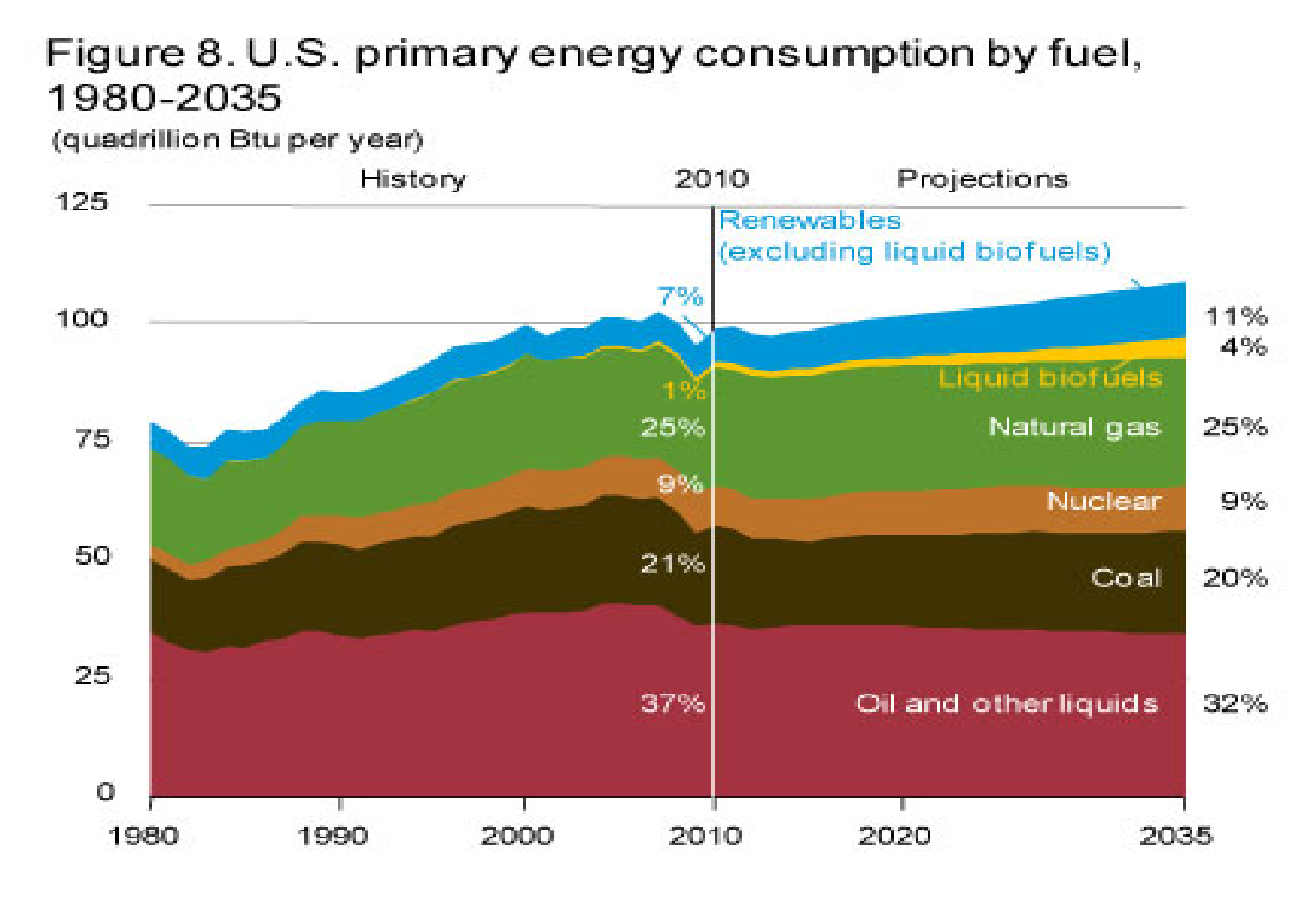

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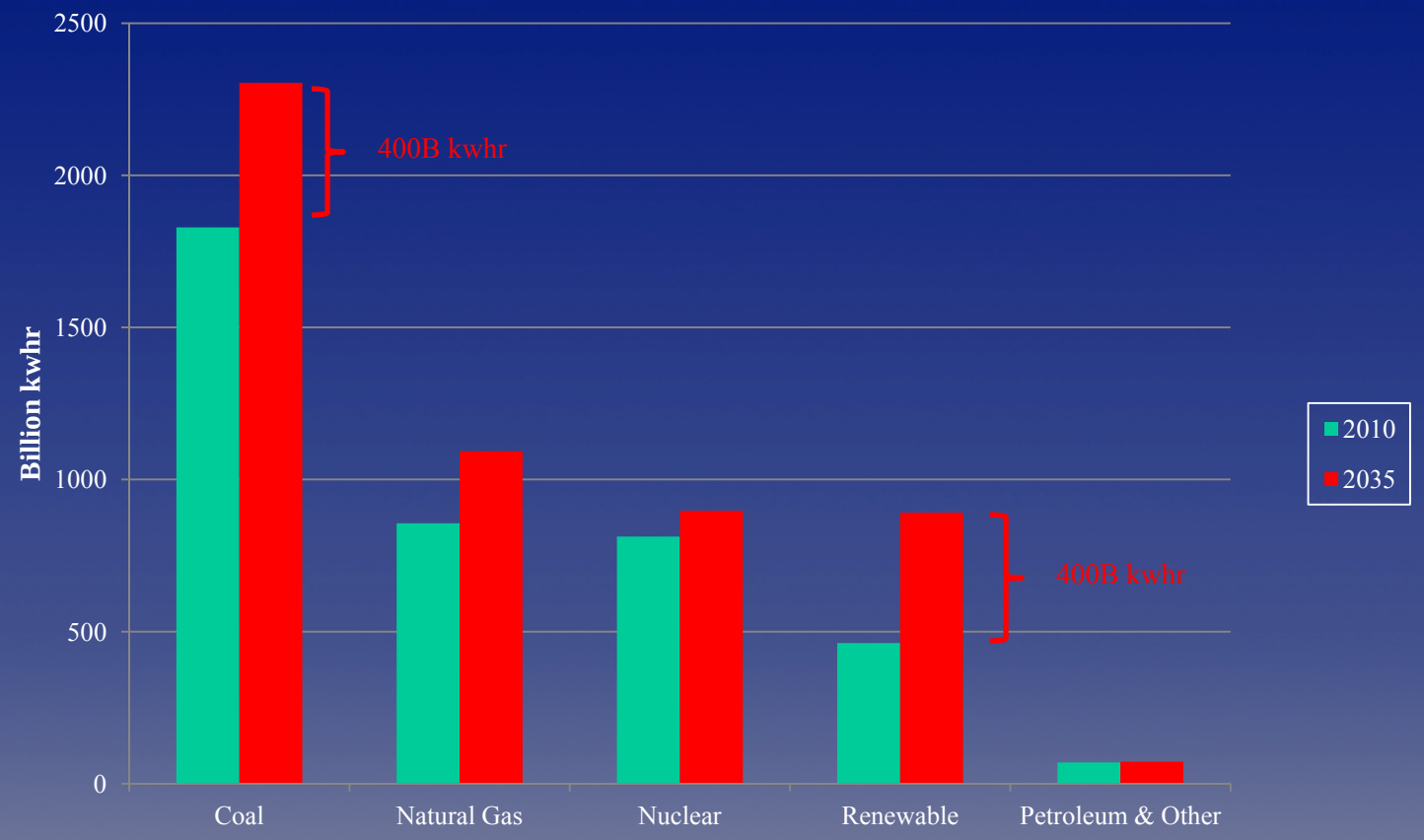
Source: EIA Annual Energy Outlook, 2012 Early Release

Electricity Generation by Fuel



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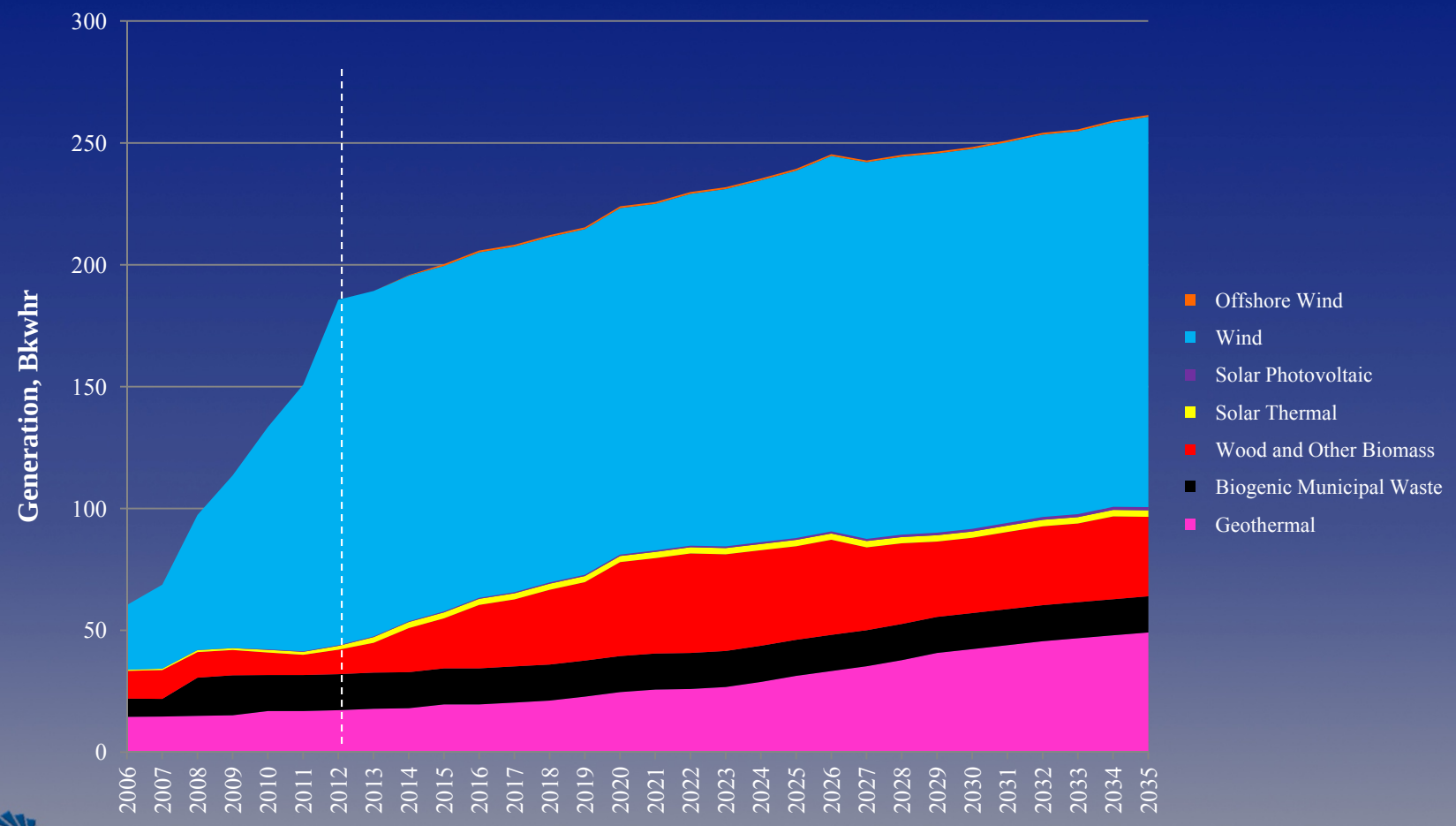
Source: EIA Annual Energy Outlook, 2010

Non-Hydro Renewable Generation



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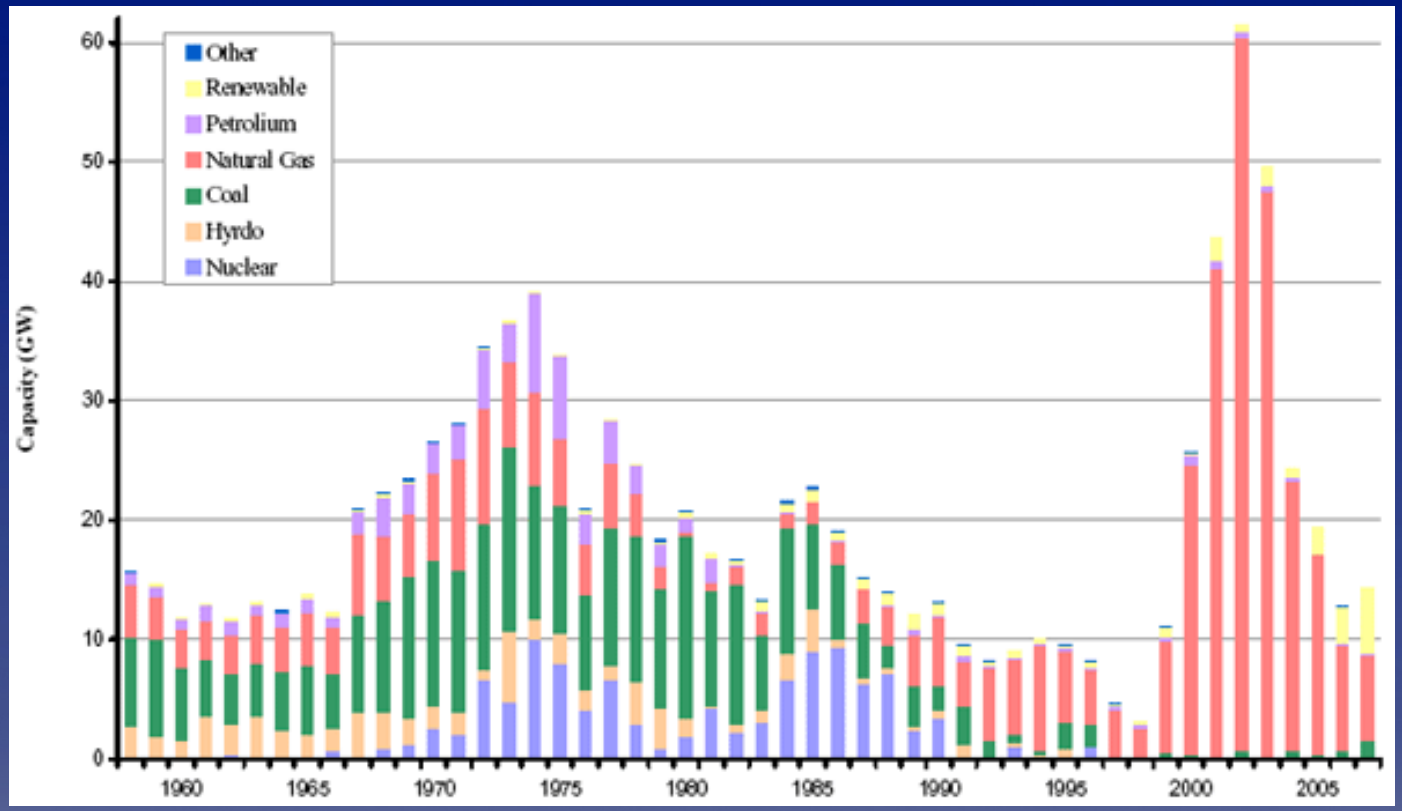
Source: EIA, Annual Energy Outlook 2012

U.S. Capacity Additions: 1958-2007



Source: Energy Velocity

Add Campaign
Funded by Chesapeake Energy
(natural gas producer)
Source: Gooden Group Public Relations

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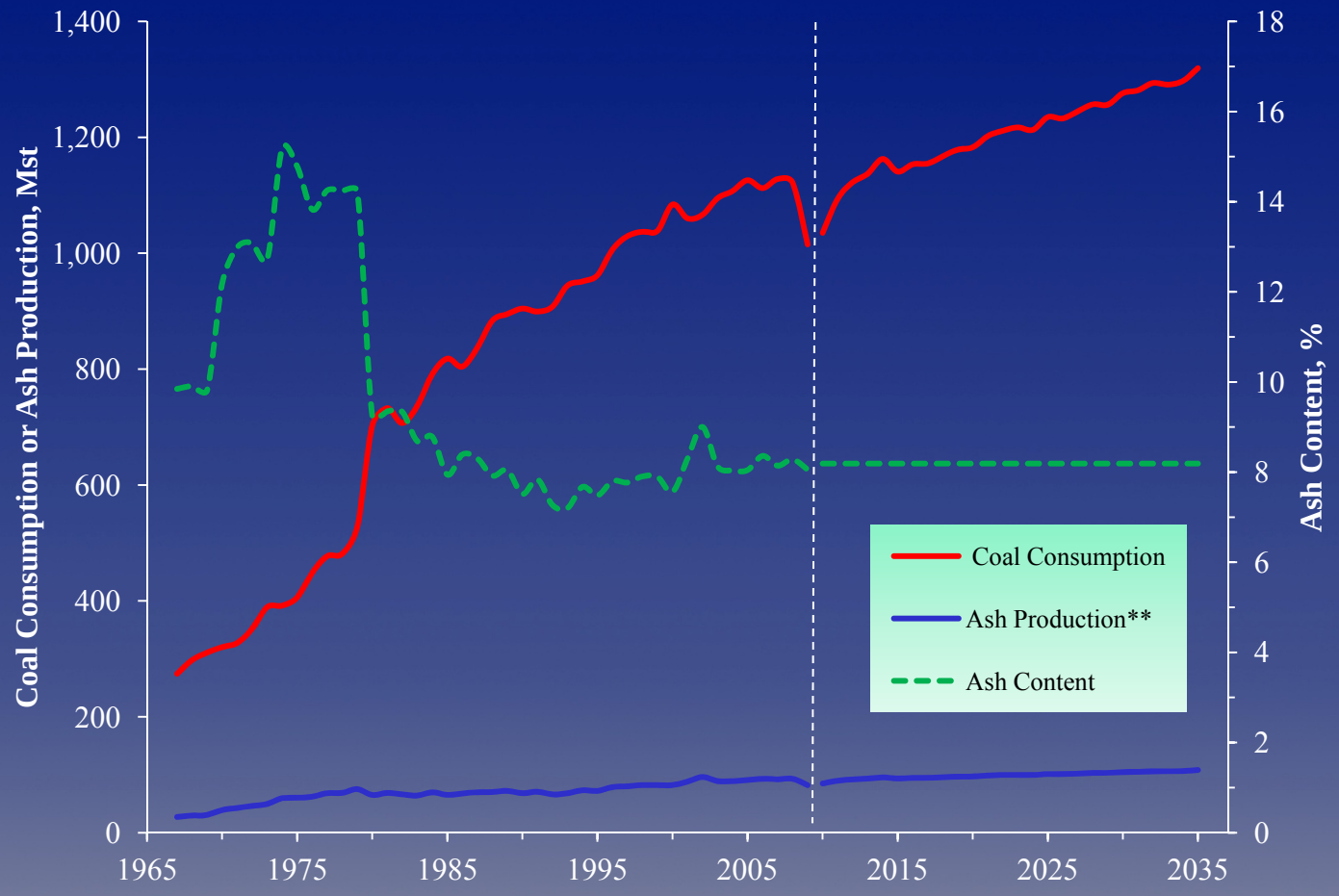
Projecting Ash Production



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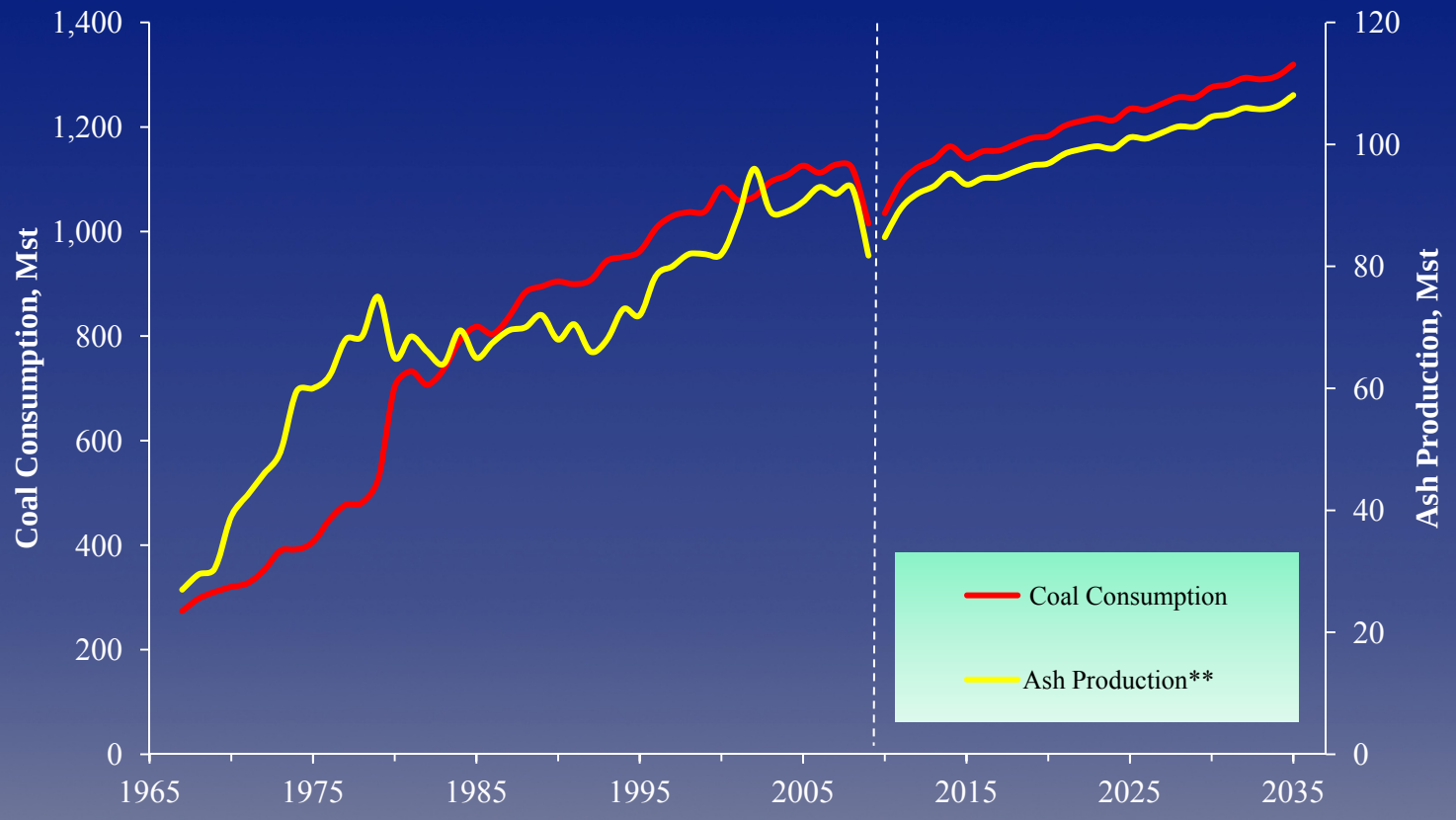
Source: ACAA, National Mining Assoc.



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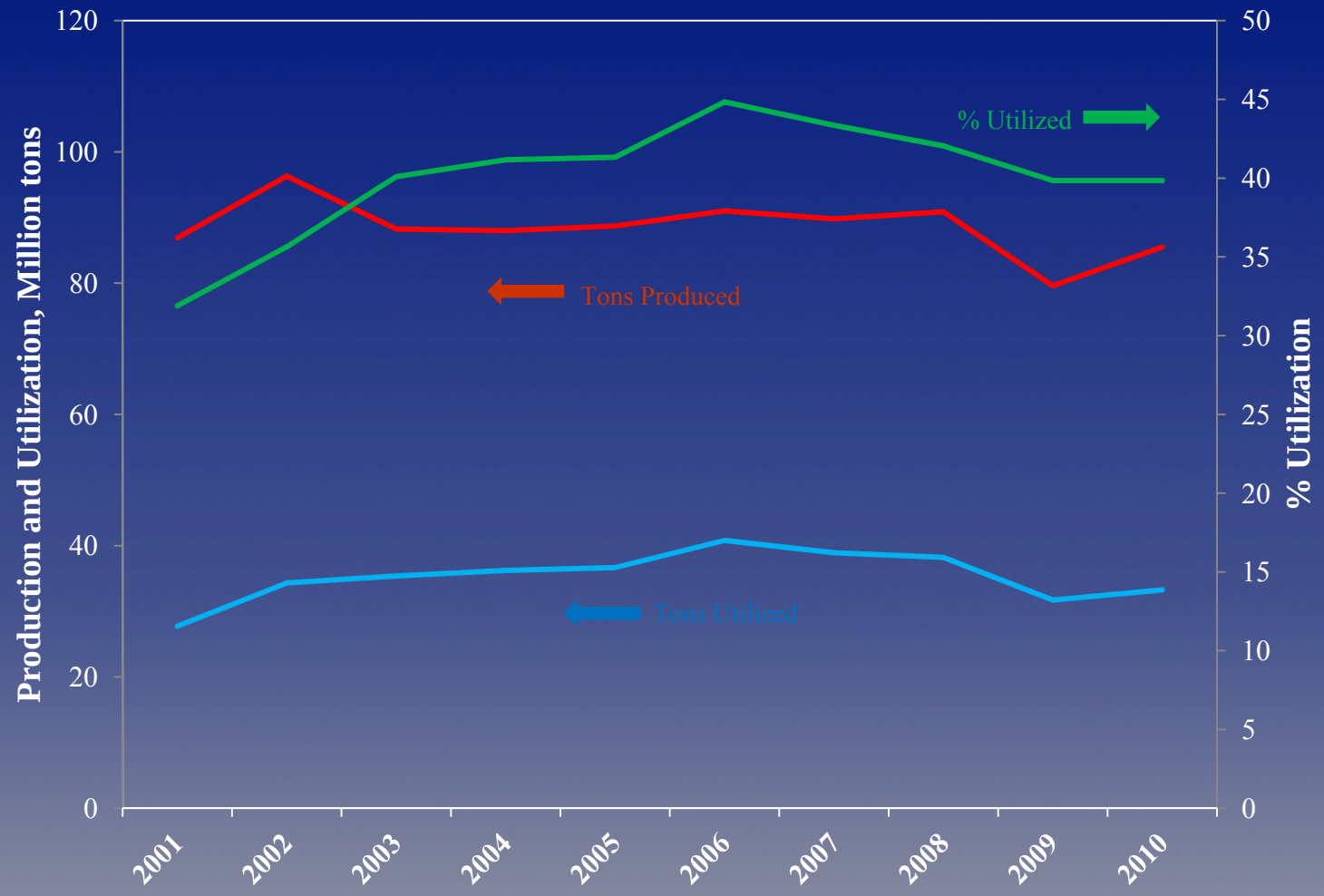
Fly Ash and Bottom Ash



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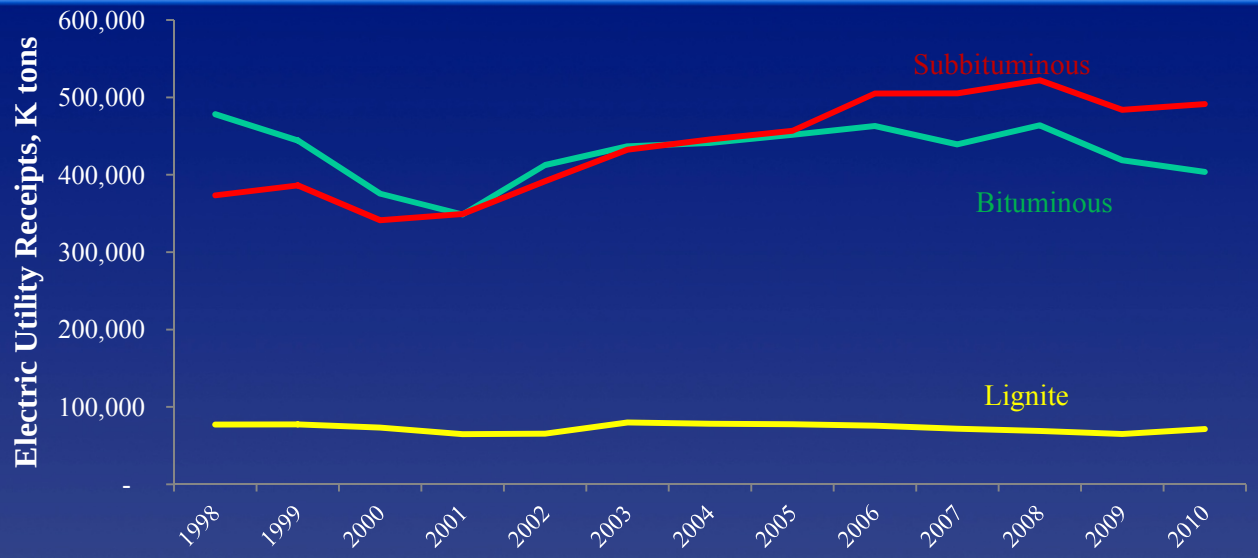
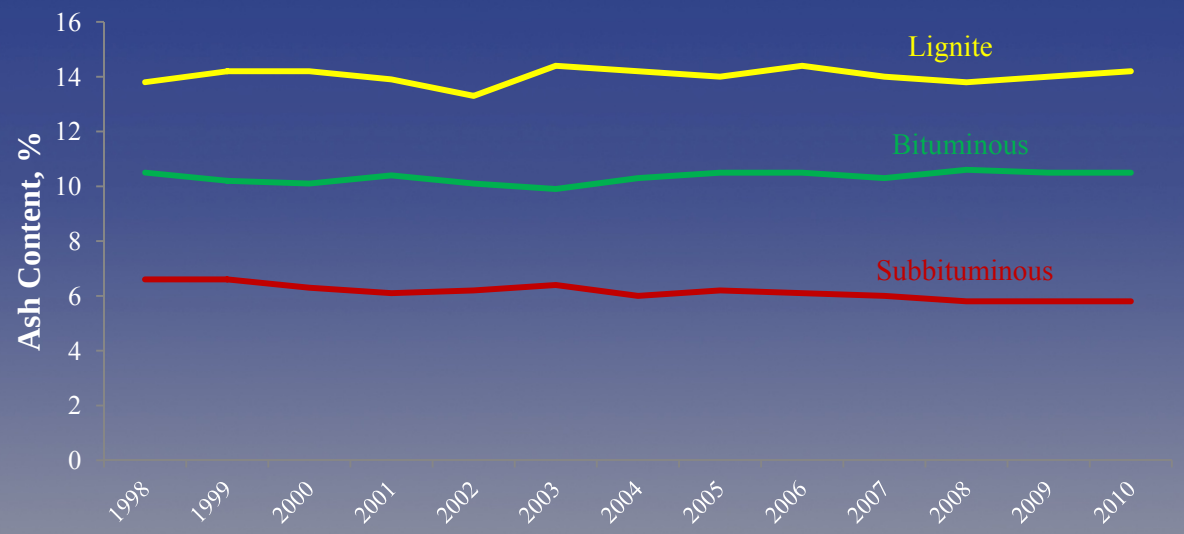
Fuel Delivered to US Utilities





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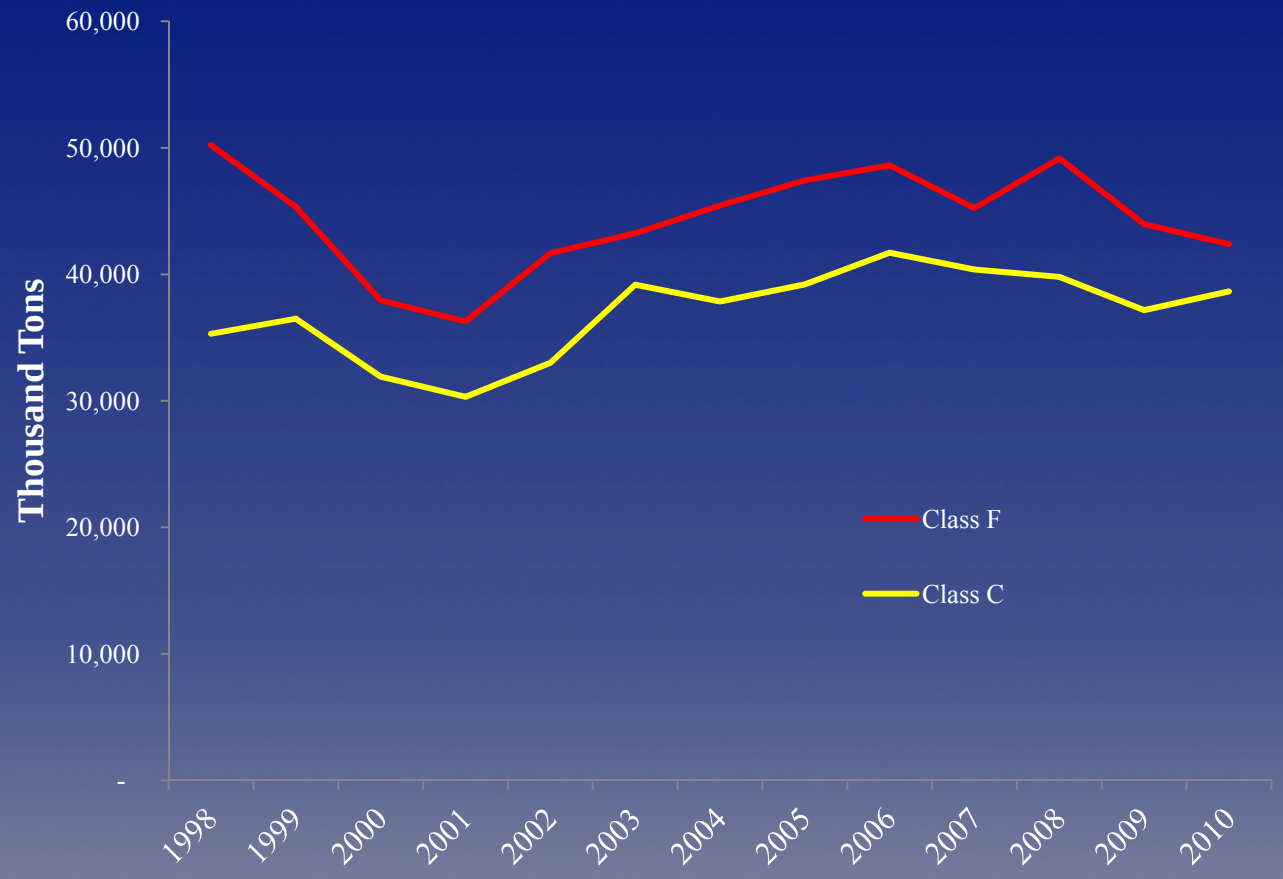
US Ash Production Estimate



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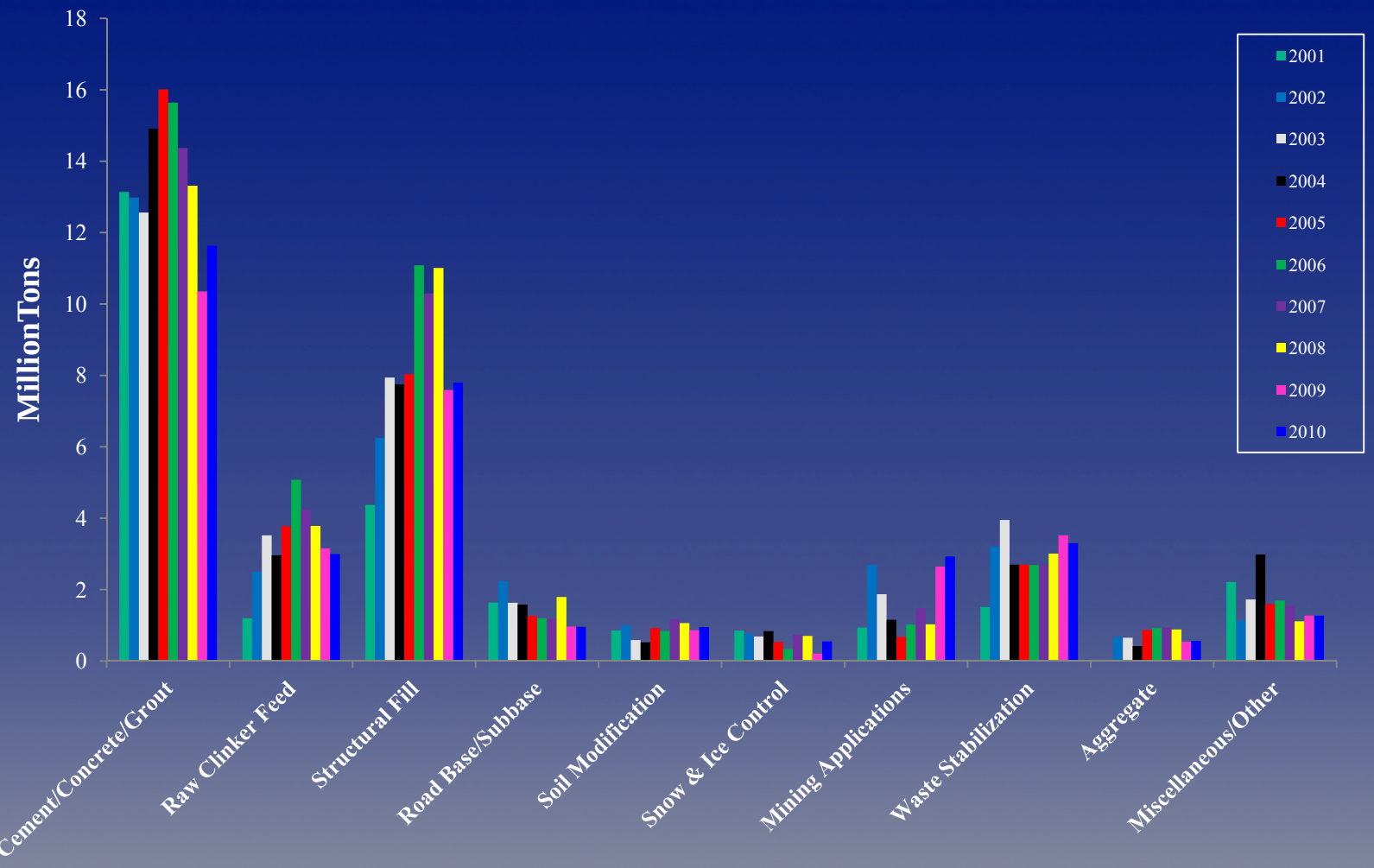
Fly Ash & Bottom Ash Major Uses



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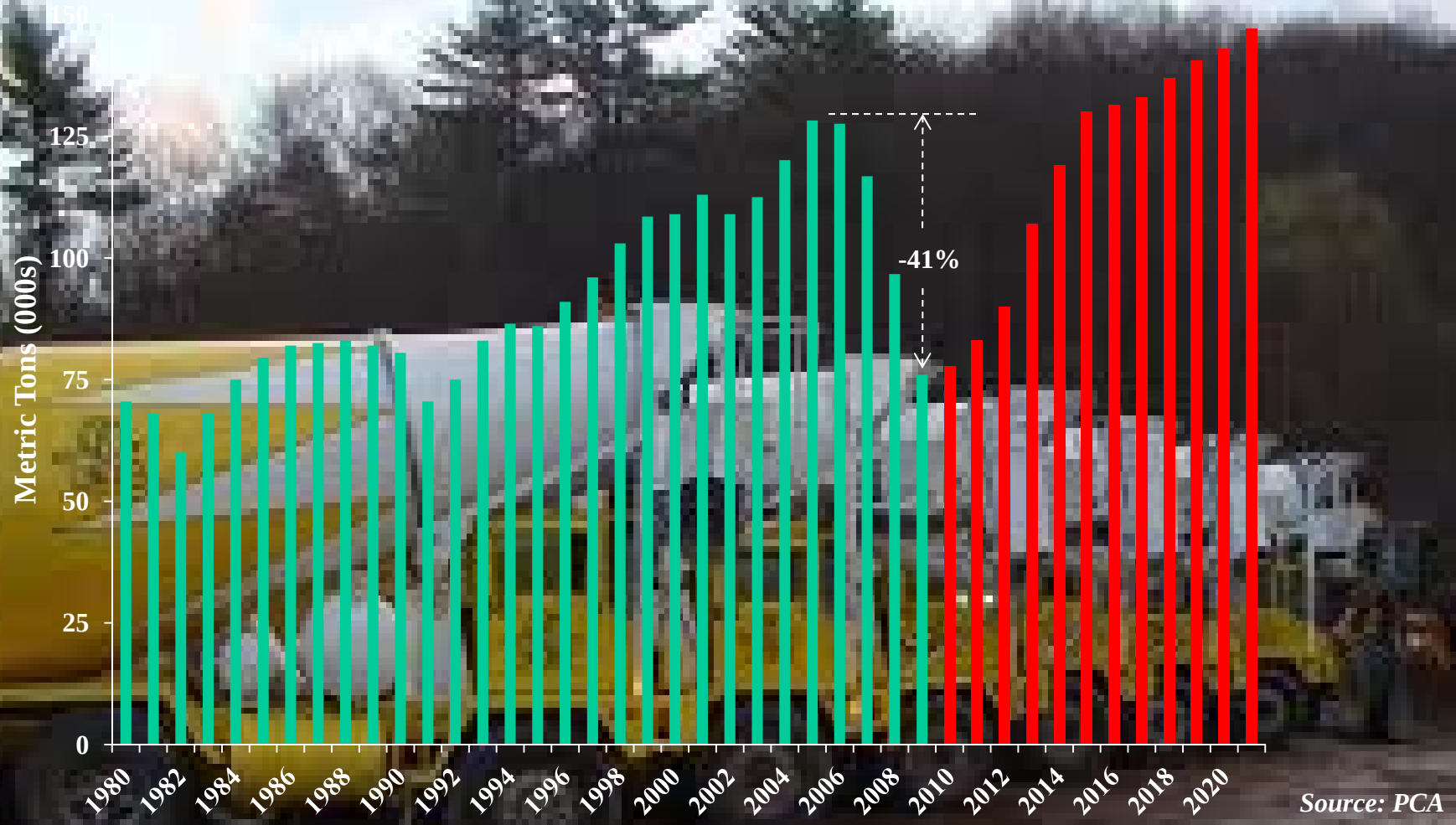
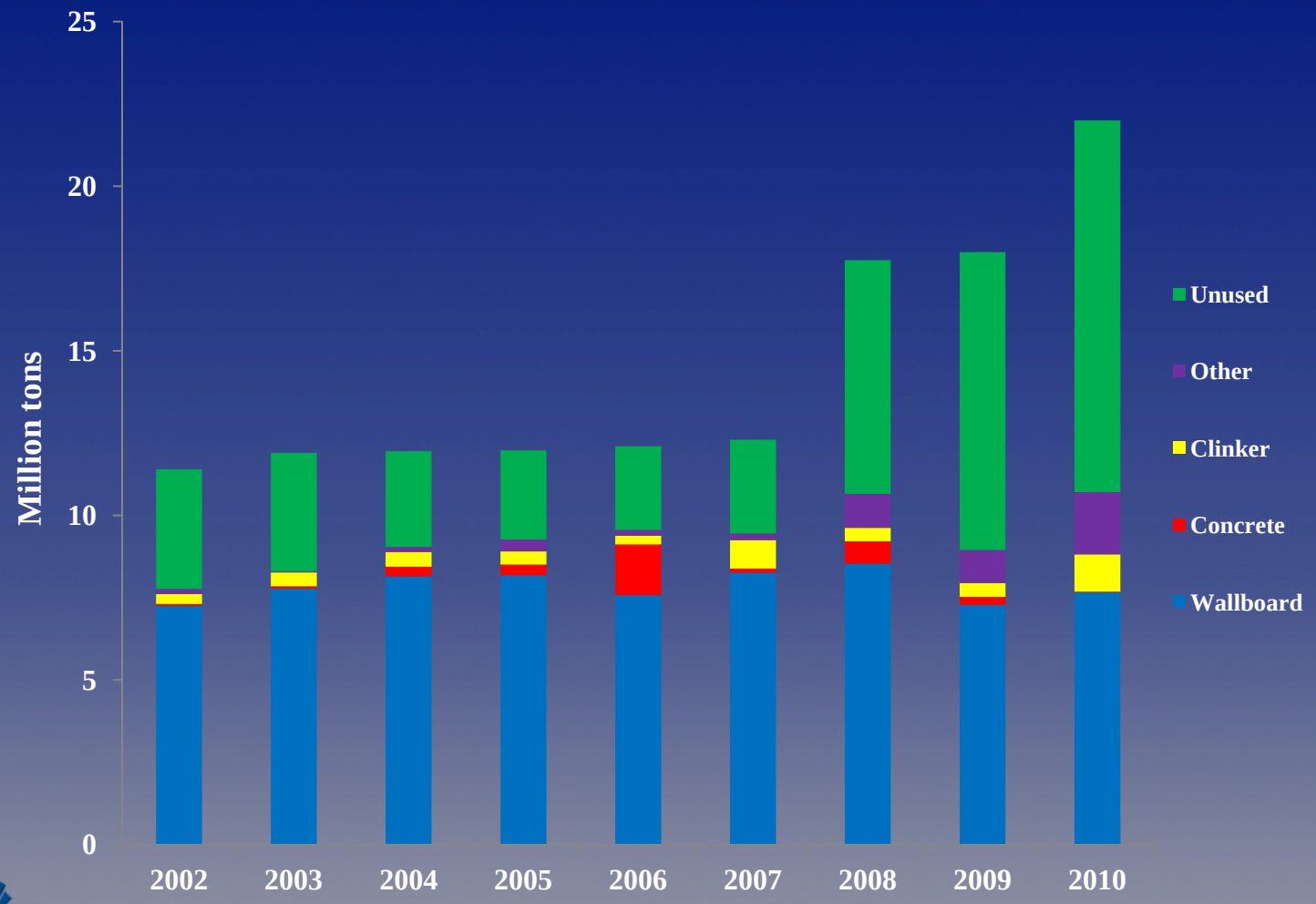
Portland and Masonry Cement Consumption



Source: PCA

FGD Gypsum



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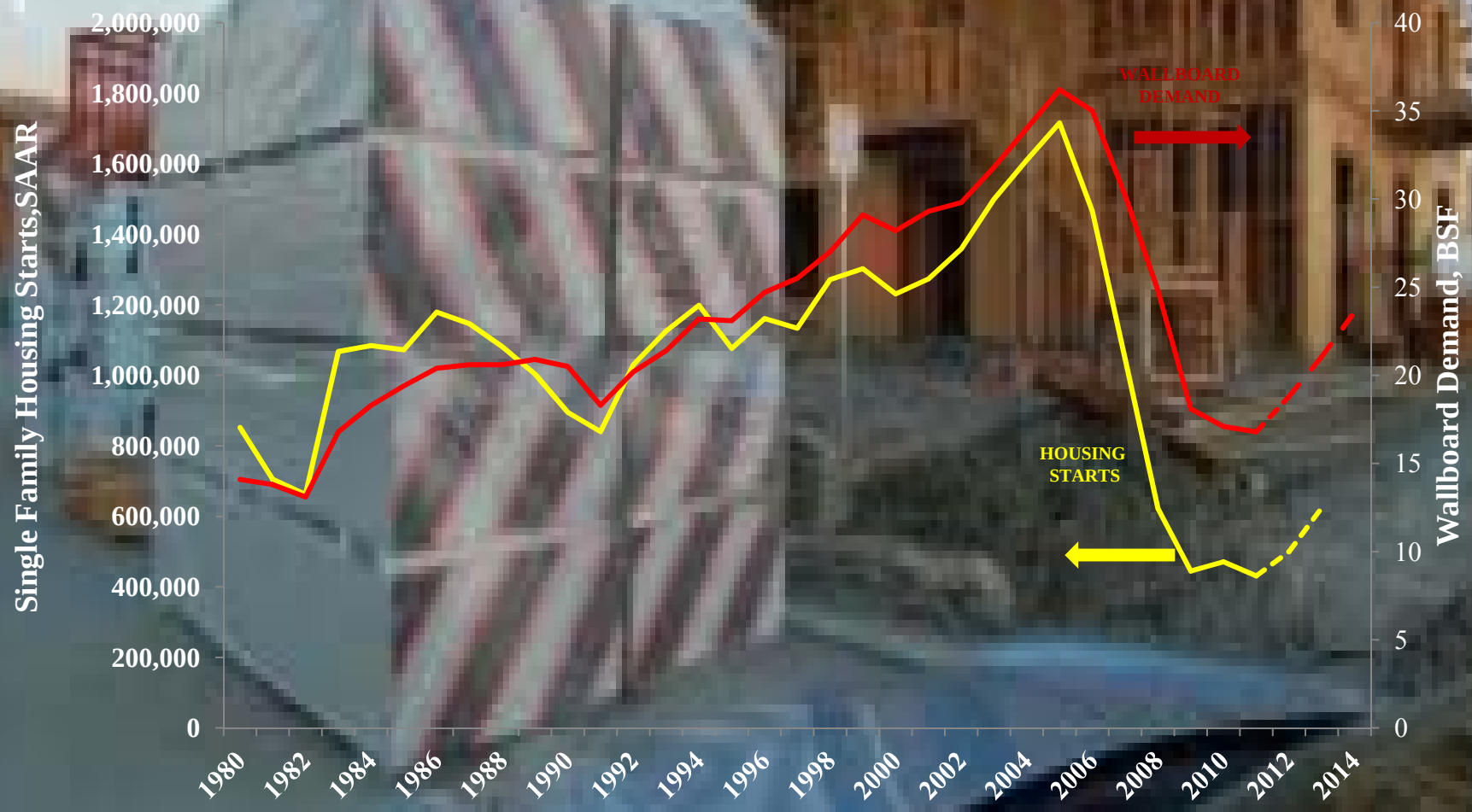
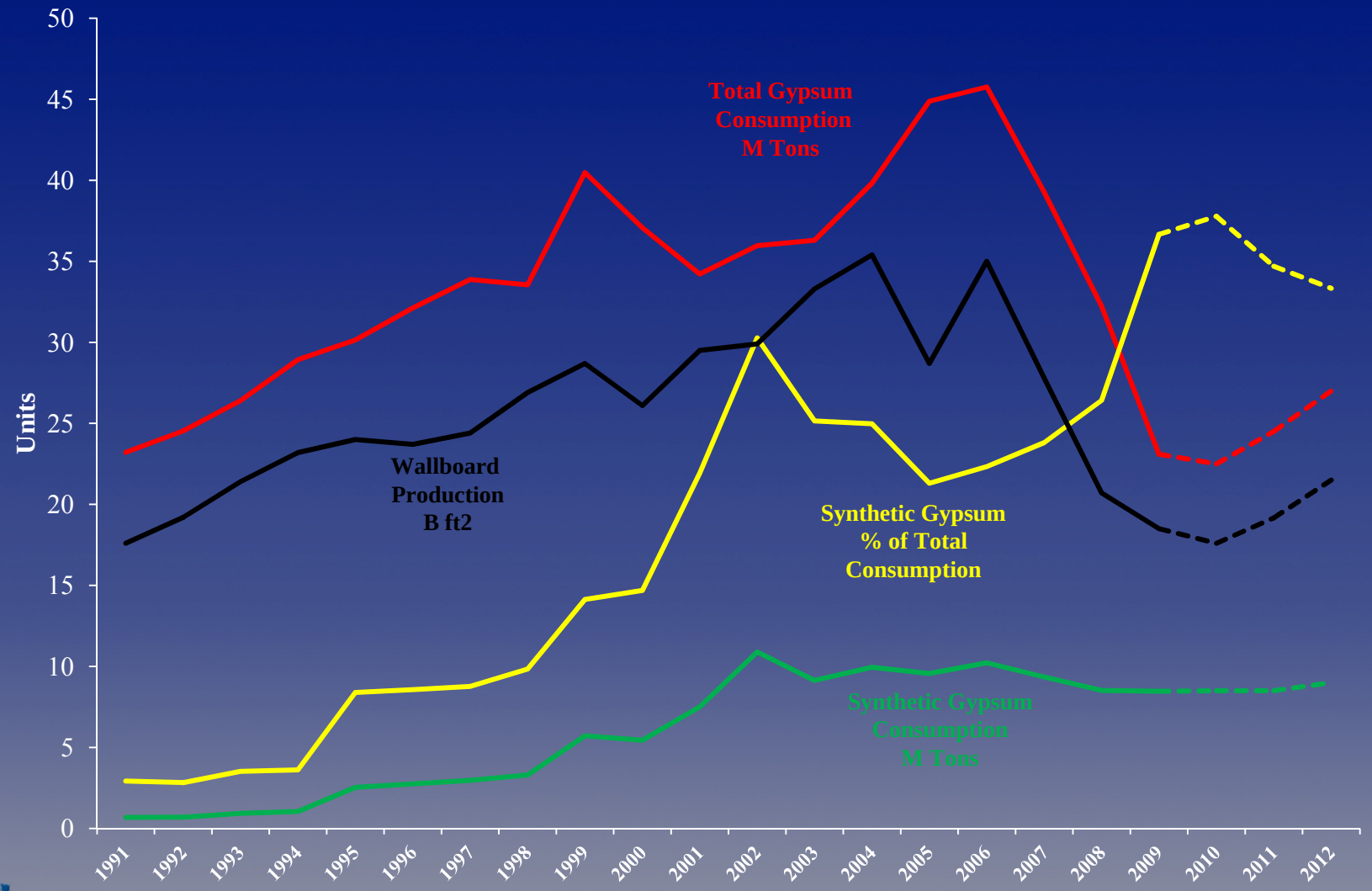
Source: ACAA

Wallboard Demand



Source: American Homebuilders Assoc

US Gypsum Production and Utilization



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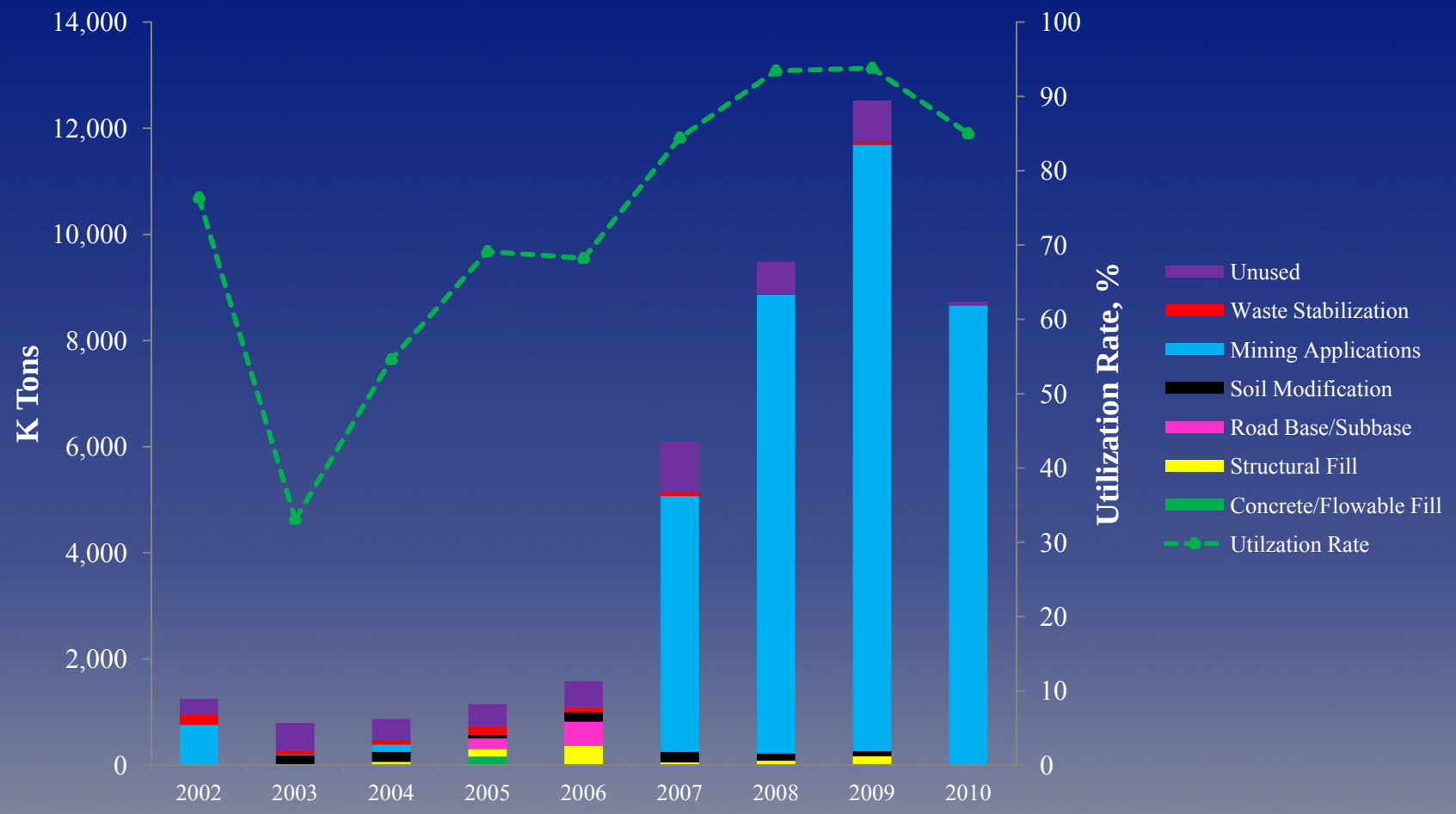
Source: USGS

FBC Ash



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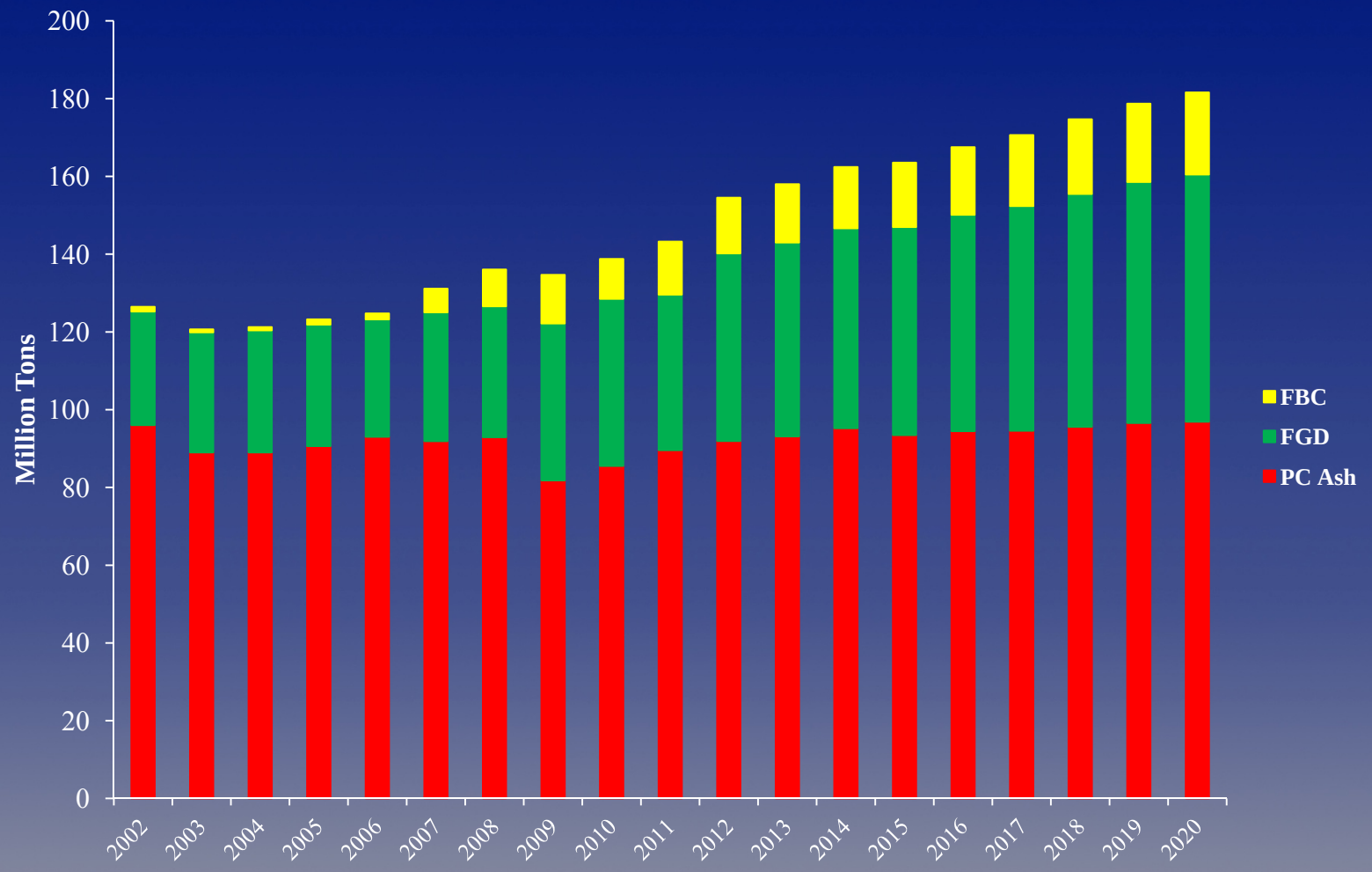
Assumptions

- Unconfined CCB uses will be curtailed and eventually eliminated by regulation
- Renewable energy growth will be realized by co-firing biomass primarily in FBC units

CCB Production Projections



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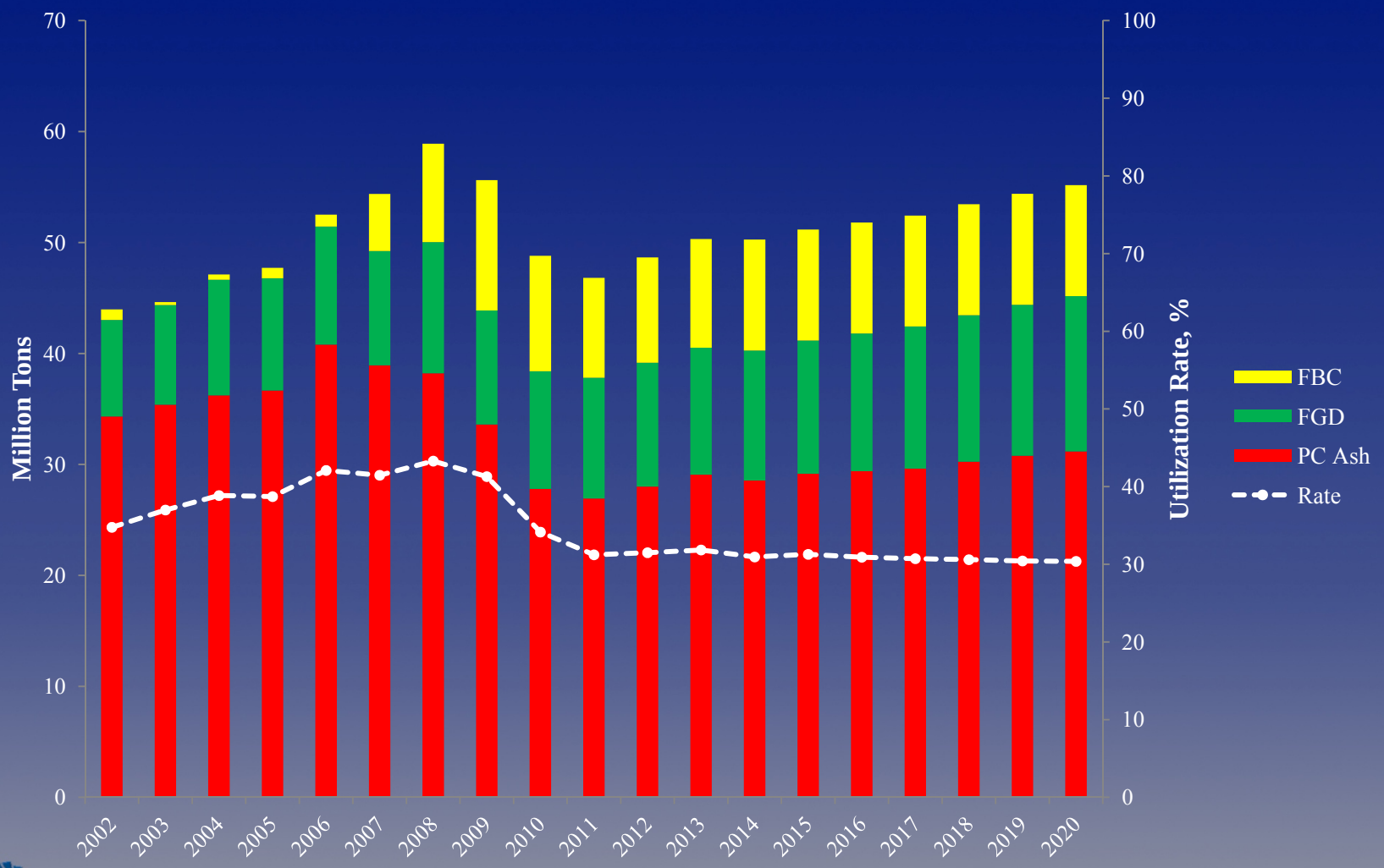
CCB Utilization Projections



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Summary Projections

		2010	2012	% Change
Coal Utilization	M tons	1,035.2	1,122.3	+8.4%
Production				
PC Ash	M tons	85.5	91.9	+7.5%
FGD Products	M tons	43.0	48.2	+12.1%
FBC Ash	M tons	10.3	14.3	+38.8%
Total CCBs	M tons	138.8	154.4	+11.2%
Utilization				
PC Ash	M tons	33.3	28.0	-15.9%
FGD Products	M tons	10.7	11.2	+4.7%
FBC Ash	M tons	8.7	5.0	-42.5%
Total CCBs	M tons	52.7	44.2	-16.1%
Utilization Rate	%	38.0%	28.6%	

Current CCP Research Efforts

- Beneficiated Ash
  - To improve concrete performance
- New cements based on CCPs
  - CSAB Cements
  - Clinkerless Cements
  - Plaster Cements

Beneficiate Ash to Reduce Water Demand

	Water %	D_{50}	Fineness (cm^2/g)
Underflow Product	95	11	-
Ghent Lab Product (20%)	93	6.0	8850
Ghent Lab Product (20%)	93	3.0	13400
Ghent Field Product (20%)	93	5.5	9680
Ghent Field Product (20%)	95	4.5	10700
Ghent Econosizer Product (20%)	93	20.3	4570
Ghent Flotation Product (20%)	93	20.3	4430
Mill Creek Product (20%)	97	4.4	11110
Coleman Product (20%)	96	7.3	7370
Trimble (20%)	98	25.8	3270
Rockport (20%)	95	13.1	6770
Mill Creek (20%)	97	17.8	4580
Micron3 (20%)	91	3.0	14600

Product Evaluations in Mortar

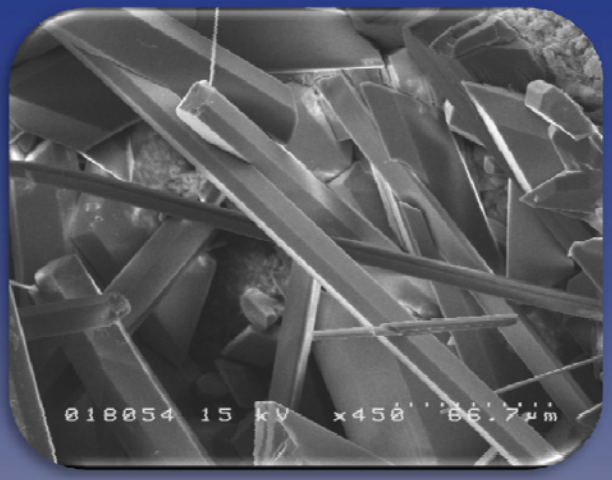
		Flowsheet 1	Flowsheet 2	Flowsheet 3	Flowsheet 4
Processed Fly Ash Product		EP	FP	UFA	FUFA
d50	microns	14.3	19.2	3.2 - 6.0	4.8 - 5.5
Water Reduction	%	96	97 - 98	93 - 95	93 - 95
S.A.I. @20% Substitution	% of Control				
	7 Day	85	80 - 85	102 - 110	102 - 107
	28 Day	100	93 - 100	129 - 135	122 - 129
	56 Day	130	103	132 - 140	126 - 133
Mortar Air	ul of AEA To Constant 6% air	620	500	700 - 1600	820 - 1180

Chloride Permeability with Processed Fly Ash

Concrete Mix	RCP (coulombs)	ASTM Chloride Rating
Control	2418	Moderate
F Ash 20%	1200	Low
Ghent CP 20%	426	Very Low
Ghent CP 40%	150	Very Low

CSAB Cements

- Not a new idea…Quillin, Mehta and others
- Purpose: To develop a calcium sulfoaluminate-belite cement (CSAB) with CFBC ash as a key ingredient
  - High strength, low-energy, and low CO_2 emitting
- Calcium sulfoaluminate (C_4A_3S`)
  - Increases early strength
  - Hydration of this phase forms ettringite
    - ($C_6A\acute{S}_3H_{32}$)
    - Contributes to early strength
- Belite (C_2S)
  - Hydrates slowly
  - Low compressive strengths compared to Alite (C_3S)



Ettringite

Formulation of CSAB Cement

- Commercially produced CSAB cement acquired from China
  - Shenzhen Chenggong Trade Co. CSA
  - Major cementitious phases and oxide compositions
    - X-ray Diffraction (XRD) and X-ray Fluorescence (XRF)
    - Klein's compound and belite need to be optimized

- Initial formulations
  - Bogue equations modified for CSAB cement
    - These normative equations could not be used
    - Minor amounts of other phases formed (*i.e. gehlenite;* C_2AS)

- Formulations adjusted to meet several objectives:
  - Minimize limestone and thus the free lime formed (CaO)
  - Maximize the byproduct used (CFBC and PCC ash)
  - Produce a cement that approaches the performance of commercial CSAB cement
    - *CSAB#1*
    - *CSAB#2*
    - *CSAB#4*

Laboratory Cement Formulations

Component	CSAB#1	CSAB#2	CSAB#4 HS	CSAB#4 MS	CSAB#4 LS
Limestone	39.1	46.0	29.6	24.6	13.7
Bauxite	15.0	15.2	30.2	25.0	13.9
FBC Spent Bed[1]	13.0	13.1	19.6	16.3	9.0
Class C Fly Ash	6.8	-	-	-	-
Class F Fly Ash	-	12.9	-	-	-
Gypsum[2]	13.3	12.8	20.6	17.1	31.7
Ultra Fine Ash[3]	-	-	-	17.1	31.7
Total CCBs	33.1	38.8	40.2	50.5	72.4

[1]Byproduct of fluidized bed combustion (FBC) of coal
[2]Gypsum and Ultra Fine Ash are milled with the clinker; ***percentage is calculated on a mass basis of the cement product***
[3]Ultra Fine Ash is a processed material from ponded, Class F fly ash

Procedure:

1. Raw materials are milled to 16 microns
2. Fired in a furnace at 1250°C for 1 hr to produce clinker
3. Clinker is milled with FGD gypsum to produce cement

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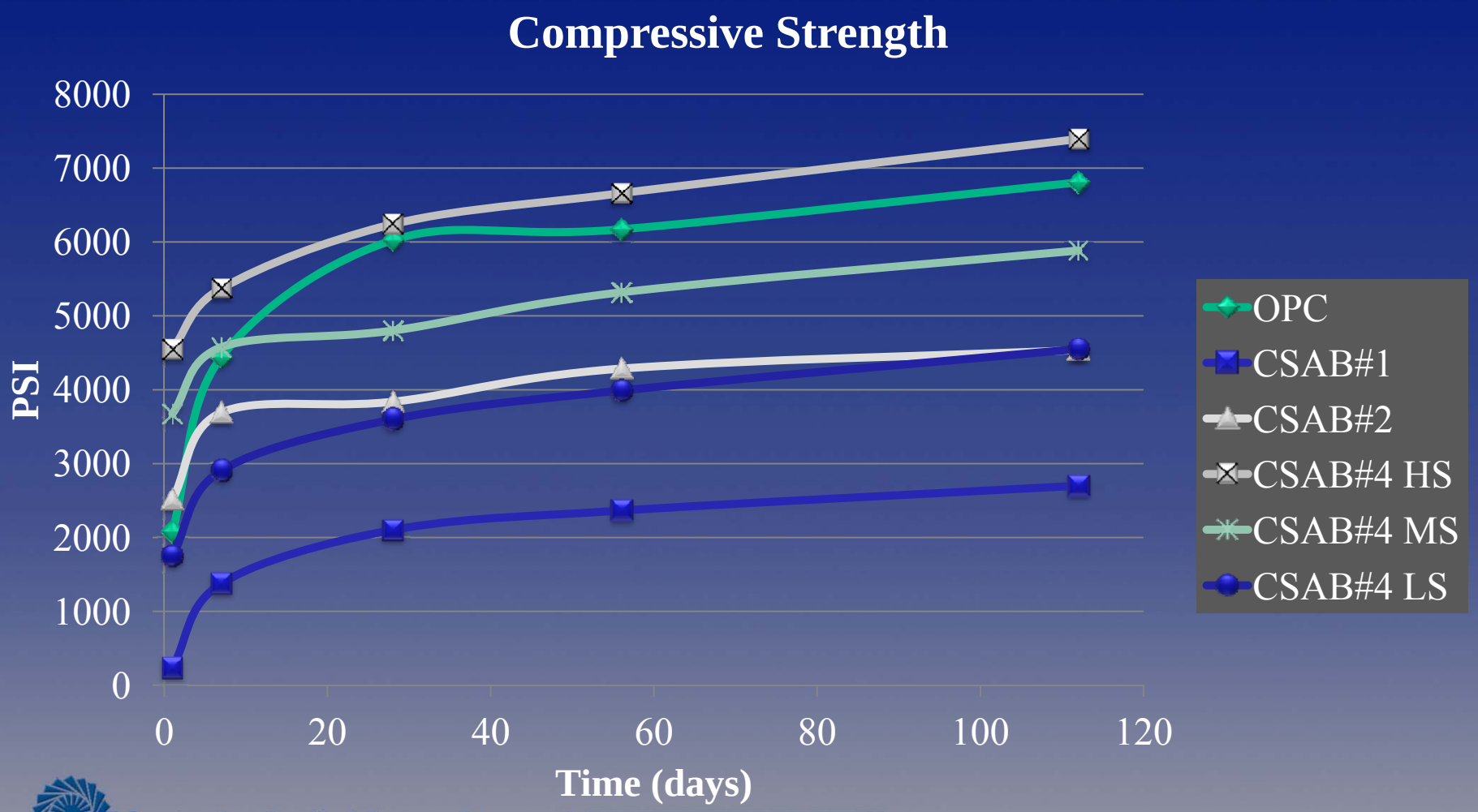
Laboratory Cement made from FBC Ash



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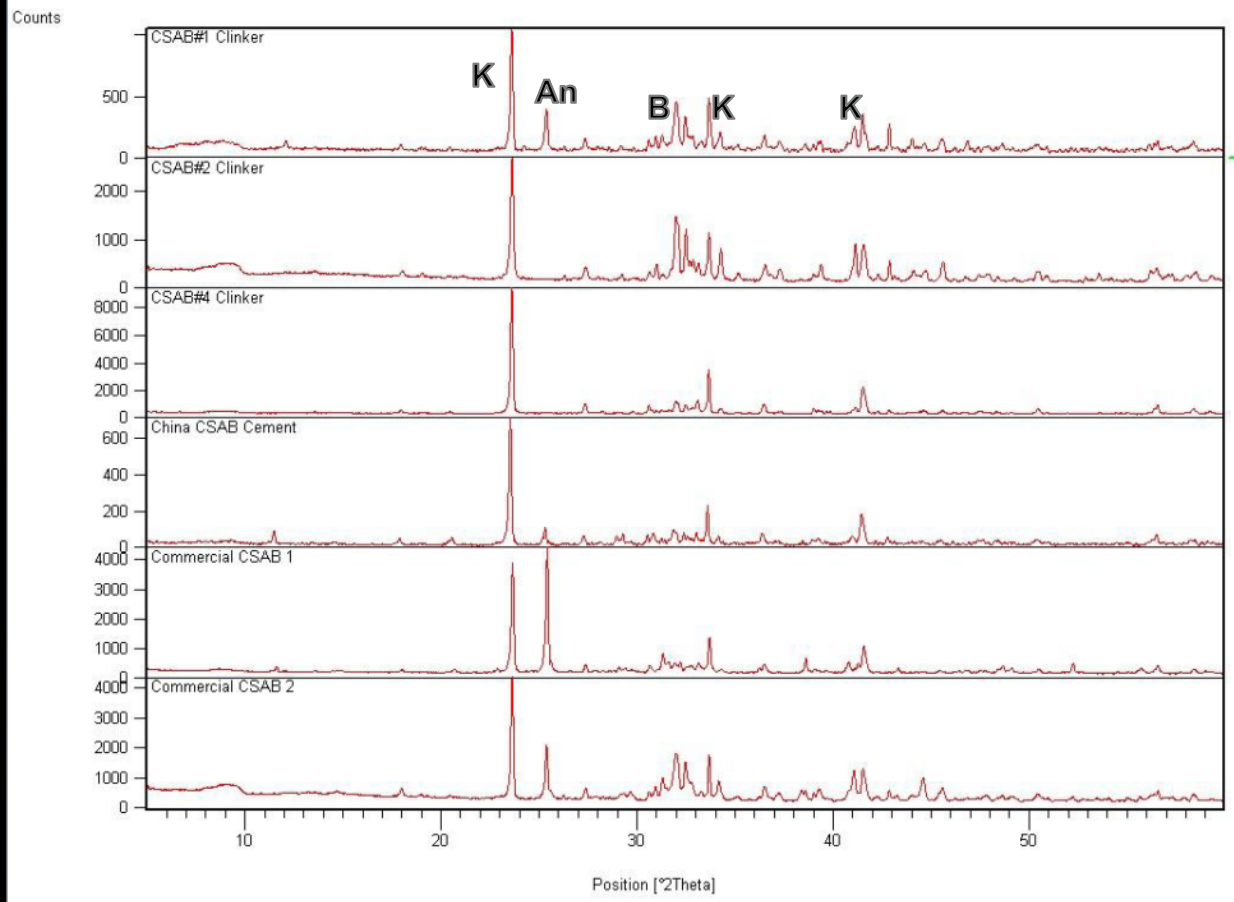
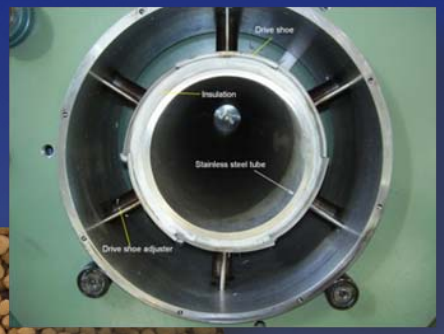
XRD Analysis of Cement Clinkers



K = Klein's Compound **An** = Anhydrite **B** = Belite

Future CSAB Work

- Large scale production of CSAB#4 for testing in concrete with new rotary kiln



- Sources of aluminum other than bauxite are being investigated (i.e. aluminum refinery byproduct)

Clinkerless Cement

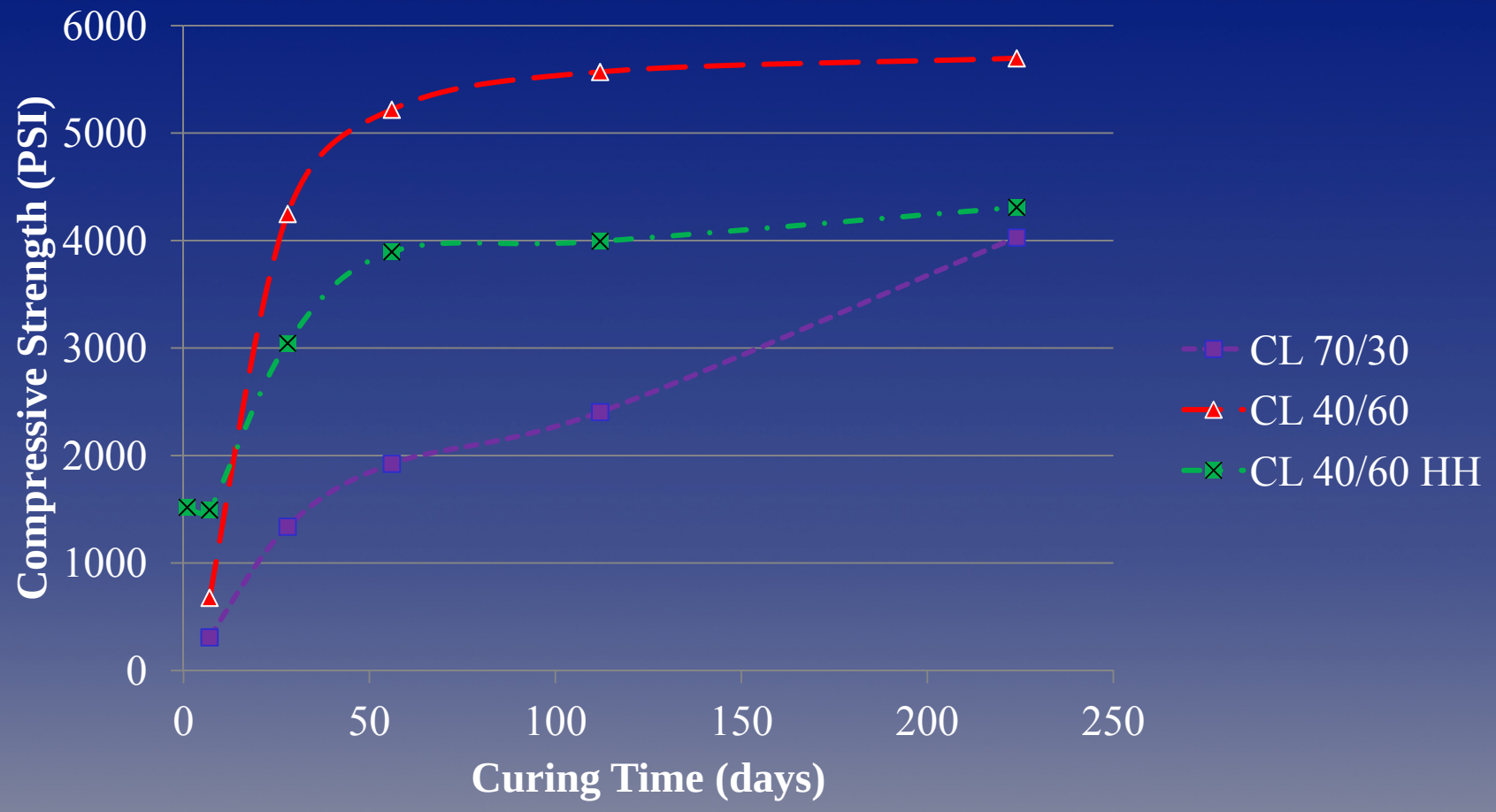
- Mainly produced from Class C fly ash and/or Clean Coal Technology byproducts
- Cementitious reactions are mainly ettringite- and pozzolan-based
- Main problems:
  - Slow strength gain
    - Calcium Sulfate Hemihydrate
  - Potential for destructive expansion
    - Excessive $Ca(OH)_2$
    - High pH
      - Colloidal ettringite crystals

Clinkerless Cement Formulation

1. Spent bed material is prehydrated with 10% water then dried
2. Material milled with fly ash to a median size of ~15 microns
3. Some formulations milled with FGD gypsum hemihydrate ("plaster") for rapid strength gain
   - Moistened with 7.5% water; pressed at 4,000 lbs (1815 kg)
   - Steam autoclave and heated 130°C and 3 bars for 4 hours

Ingredient	Formulation (% by weight)				
	FBC:UFA 70:30	FBC:UFA 40:60	FBC:UFA 40:60 HH	FBC:FA 50:50	FBC:FA 50:50 HH
FBC Spent Bed	70	40	21	50	26.5
Ultrafine Fly Ash	30	60	32	0	0
Ordinary Fly Ash	0	0	0	50	26.5
Hemihydrate	0	0	47	0	47

Mortar Strength Data for Spent Bed and Class F UFA



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Plaster Cements

- All are based on calcium sulfate
- Many varieties
  - Alpha hemihydrate: produced by heating gypsum in autoclave
- Rapid hardening, but poor durability
- Cementitious reactions produce gypsum:

Plaster: $CaSO_4 \cdot 0.5H_2O + 1.5H_2O \longrightarrow CaSO_4 \cdot 2H_2O$

ASTM C 109 Compressive Strength Data for FBC:Fly Ash:Plaster Mortars

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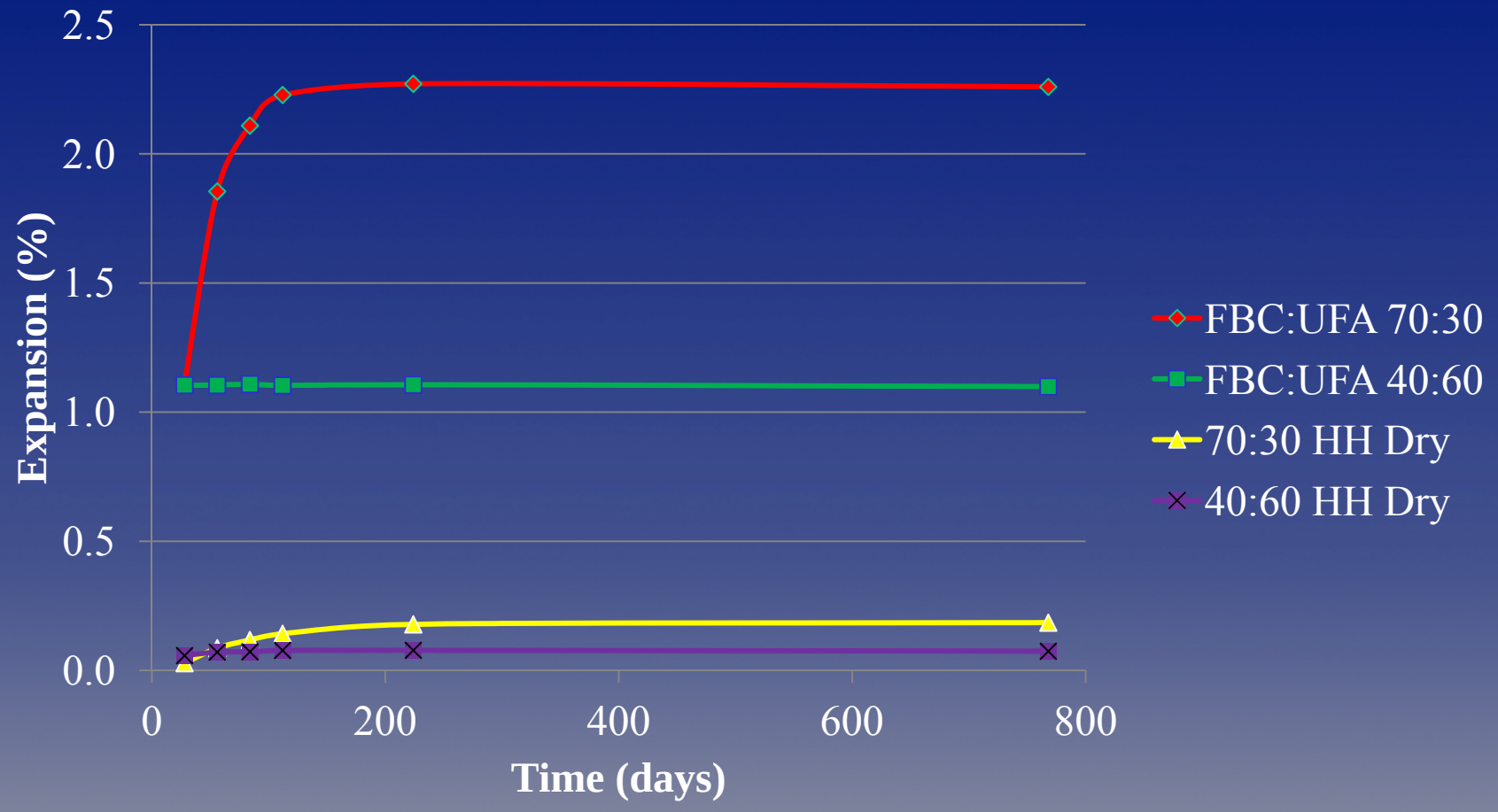
ASTM C 157 Expansion of FBC:UFA Mortars



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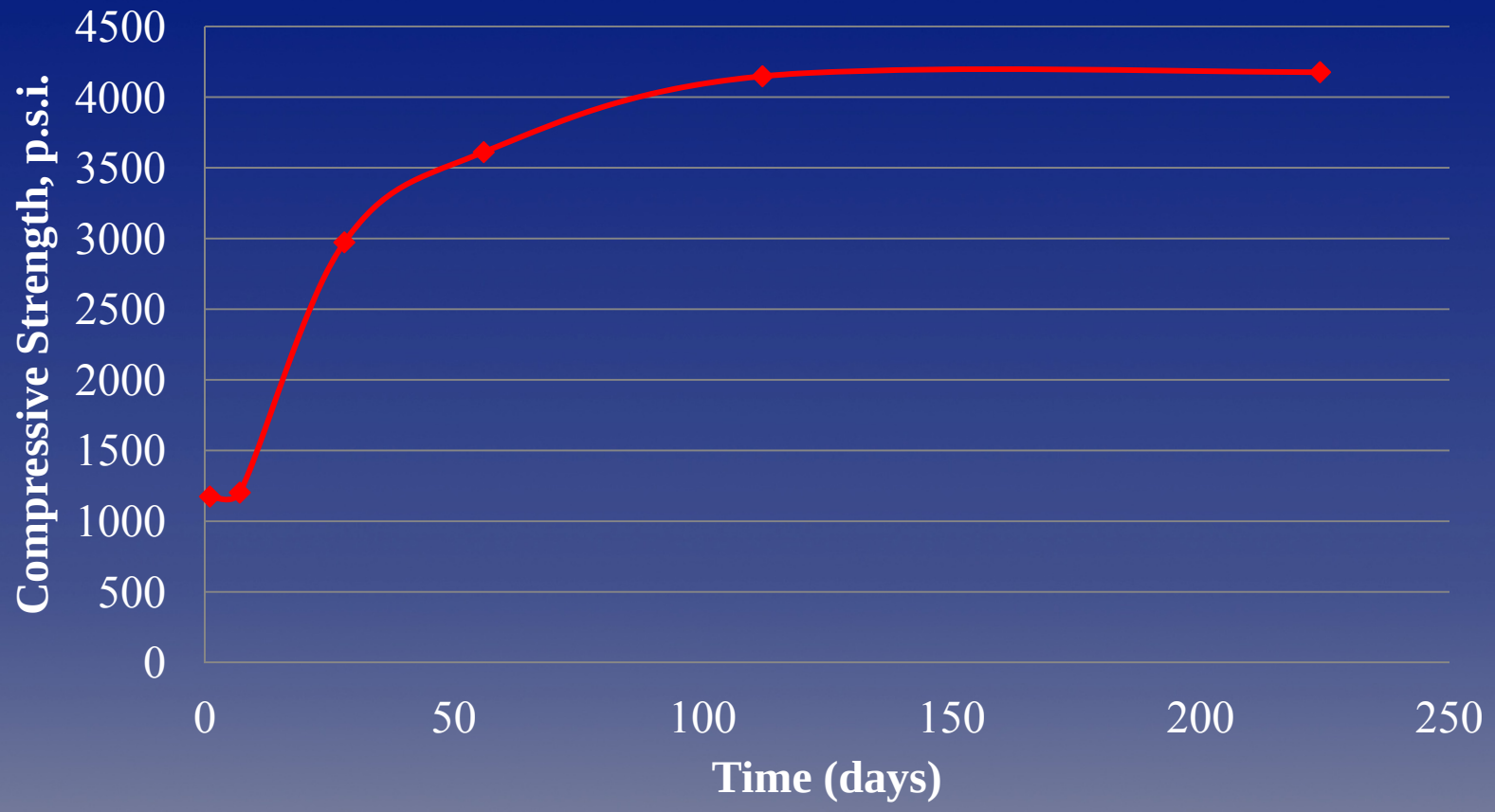
ASTM C192/C 39 Compressive Strength of FBC:UFA 40:60 HH Concrete



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ASTM C 666 Freeze Thaw Resistance