Development of Sustainable Greener Concrete By Utilizing Industrial By-Products

By

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North Cyprus

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ULUSLARARASI KIBRIS ÜNİVERSİTESİ

Patiala, 330 km from Delhi

Academic Experience

- Senior Professor of Civil Engineering having 33+ years of experience
  - Senior Professor since 2010
  - Full-Professor (2003-2010)
  - Assistant Professor (1994-2003)
  - Lecturer/Assistant Lecturer (1989-1994)

Invited Professor/Distinguished Professor

- University of South Australia, Adelaide, *Australia*
- University of Melbourne, *Australia*
- University of La Rochelle, *France*
- University of Wisconsin, Madison, *USA*
- KMUTT, *Bangkok*
- University of Western Sydney, *Australia*
- ENS Cachan, *France*
- BAM Berlin, *Germany*
- Consolis Technology, *Finland*
- INSA Rennes, *France*
- University of Wolverhampton, *U.K.*
- University of Cergy Pontoise, *France*

Research Achievements/Contributions

- *Rated amongst the top 15 globally, in my research area, having Citations 18500+ with H-Index of 72*

Editor of Journals

- *Editor, Construction and Building Materials (Elsevier)*
- *Associate Editor*, Journal of Materials in Civil Engineering (ASCE)
- *Associate Editor*, European Journal of Environmental & Civil Engineering (Taylor & Francis)
- *Associate Editor,* Journal of Sustainable Cement-Based Materials (Taylor & Francis)
- *Associate Editor*, Journal of King Saud University (Engineering)
- *Editorial Board Member,* Resources, Conservation and Recycling (Elsevier)
- *Editorial Board Member, Journal of Building Engineering* (Elsevier)

Invited Lectures

North America

- University of Wisconsin, Milwaukee, *USA*
- Pennsylvania State University, Philadelphia, *USA*
- Auburn University, *USA*
- University of Sherbrooke, Canada
- University of Wisconsin, Madison, *USA*
- University of Guanojuato, *Mexico*
- Widener University, Philadelphia, *USA*
- Concordia University, Montreal, *Canada*

Europe

- EPFL, Lausanne, *Switzerland*
- ENS Cachan, France
- INSA Rennes & INSA Toulouse, *France*
- University of Cergy Pontoise, *France*
- BAM, Berlin, *Germany*
- Queens University, Belfast, *U.K.*
- Consolis Technology, Rusko, *Finland*
- University of Bath, Bath SPA, *U.K.*
- University of Wolverhampton, *U.K.*
- Politecnico di Milano, Milan, *Italy*
- Ghent University, Ghent, *Belgium*
- University of Aveiro, *Portugal*
- Poly-technical University of Valencia, *Spain*
- University of Oviedo, *Spain*
- *Warsaw University of Technology, Warsaw, Poland*
- *Lublin University of Technology, Lublin, Poland*

Australia/New Zealand

- University of South Australia, Adelaide
- University of Melbourne, *Melbourne*
- Western Sydney University, *Sydney*
- University of Southern Queensland, *Toowoomba*
- University of Southern Queensland, *Sprinfield*
- University of New Castle, *New Castle*
- University of Canterbury, *Christchurch*

China/Hong Kong

- Hong Kong University of Science & Technology (HKUST), *Hong Kong*
- Tongji University, Shanghai & Hunan University, Changsha, *China*
- South China University of Technology, Guangzhou, *China*

Africa

- 2iE, Ouagadougou, Burkina Faso
- *Botswana International University of Science and Technology, Botswana*

Others

- Istanbul Technical University, Istanbul, *Turkey*
- American University of Sharjah, *UAE*
- Gadjah Mada University, Yogyakarta, *Indonesia*
- King Saud University, *Riyadh, Saudi Arabia*
-

Solid Waste

- Any material that we discard, which is not liquid or gas, is the solid waste
  - Municipal Solid Waste (MSW):
    - Solid waste from home or office
  - Industrial Solid Waste (ISW):
    - Solid waste produced from Mines, Agriculture or Industry
    - Agriculture wastes
- Solid waste management has become one of the global environmental issue, due to:

  Continuous increase in industrial globalization and waste generation

Waste Generation

- **Municipal Solid Waste:** In 2020, world generated about **2.24 billion tons** of municipal solid waste. Worldwide, waste generated per person per day averages 0.79.

- **Industrial Solid Waste:** Approximately **7.6 billion tons** of industrial solid waste

- **Construction & Demolition (C&D) Waste:** Over **10 billion** tons yearly.

- **Agriculture Waste:** **Over 6 billion tons**

- **Major industrial solid wastes generators:**
  - — Thermal power plants (coal ash)
  - — Steel and Iron industry (blast furnace slag, foundry sand)
  - — Non-ferrous industries (red mud, silica fume, copper slag)
  - — Cement industry (cement dust)
  - — Wood product industry (wood ash)
- **Disposal of industrial by-products is becoming an increasing concern:**
  - — Lack of land filling space
  - — Increasing cost of land filling
  - — Leaching of toxic components and heavy metals
- **Utilization of industrial by-products is an attractive alternative to disposal**

Approach for Managing Industrial By-products & Waste Materials

- **Reduce, reuse, recycle**
- **Waste prevention**
- **Burying, burning, shipping**

Useful By-Products

- Coal-combustion products
- Wood ash
- Municipal solid waste ash
- Municipal sludge ash
- Iron Slag
- Plastics & Scrap Tires
- Demolition debris
- Metallurgical by-products, including silica fume
- Agricultural by-products ash
- Pulp and paper industry by-products
- Foundry by-product
- Blast furnace slag
- Copper & Iron Slag
- Recycled asphalt pavement
- Waste Glass
- Recycled concrete for aggregates

By-Products/Waste Generation

Type of By-Products	Production/Generation (Million tons)	Utilization (Million tons)
Coal Combustion By-products	1221.9	677.7
Waste Glass	130	28
MSW Ash	150	
Waste Plastics	360	50
Waste Foundry Sand	106	-
Iron Slag	380	
Steel Slag	270	
Copper Slag	38	
C& D waste	10000	
Scrap Tires	1000 millions tires	100 million tires

The Great Economist Adam Smith once said:

- The matter in all its myriad forms and manifestations is immortal. It never loses its entire utility; it only changes its form after every consumption-process. It simply undergoes a metamorphosis.

- This, according to him, is the immutable law of Nature. **This dictum applies to industrial by-products.**

Benefits of Using Industrial By-Products

- **Environmental benefits:** Reduced need for disposing in landfills; Reduces the use of raw materials; Reduces greenhouse gas emissions

- **Economic benefits:** Reduced costs associated disposal; Savings from using as substitute alternate materials in place of more costly materials

- **Product benefits:** Improved strength and durability of materials.

By-Products Covered in this Presentation

- Coal Bottom Ash (CCPs)
- Waste Foundry Sand (a.k.a. Spent Foundry Sand)
- Waste Glass

Coal Combustion Products (CCPs)

Coal combustion products (CCPs) are the by-products generated from burning coal in coal-fired power plants.

- Fly ash
- Bottom ash
- Boiler slag
- Flue Gas Desulfurization (FGD) Material a.k.a. Clean-Coal Ash

Country/Region	CCPs Production (Million Tons)	CCPs Utilization (Million Tons)
Australia	12.3	5.4
Canada	4.8	2.6
China	565	396
Europe	40.3	38
India	197	132
Japan	12.3	12.3
Middle East & Africa	32.2	3.4
USA	107.4	60.1
Other Asia	18.2	12.3
Russia Federation	21.3	5.8
TOTAL	777.1	415.5

Global Fly Ash generation and utilization, 2016
(www.coalttans.com)

Coal Bottom Ash

- Coal ash extracted from the flue gases in the electrostatic precipitators is called fly ash (80% of coal ash).
- Coal ash collected at the bottom of furnace is called coal bottom ash (approximately 20% of coal ash).

Factors affecting the properties of coal ash

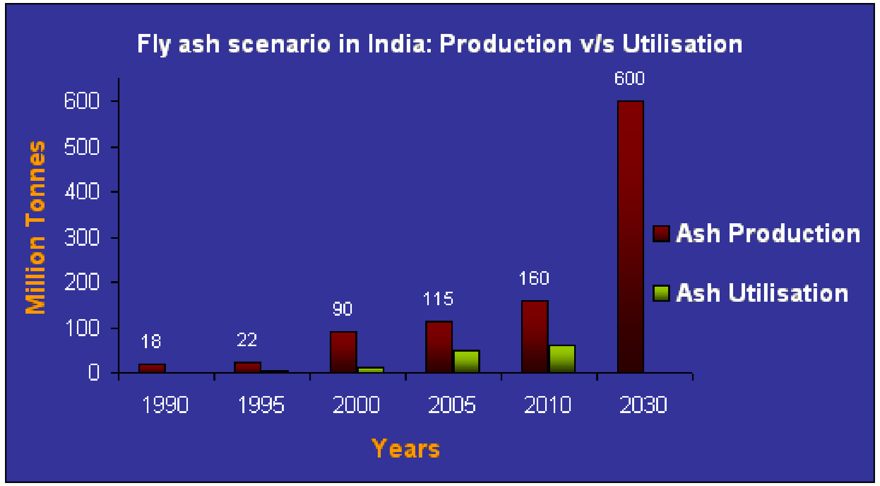
- Source of coal
- Degree of pulverization of coal
- Firing temperature in the furnace
- Type of furnace

Indian Coal Ash

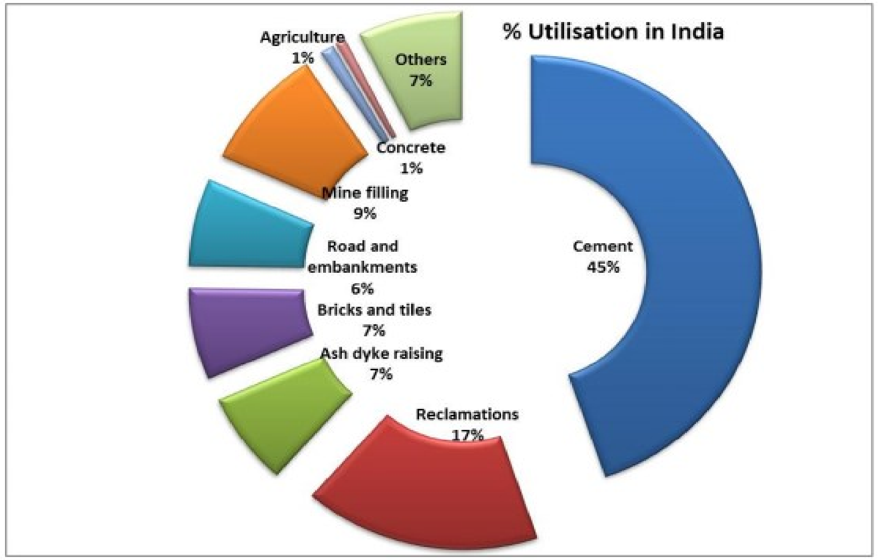
- During 2014-15, 554 million tons of coal was burnt and about 184 million tons of coal ash was produced by 143 coal fired thermal power plants.

- Out of 184 million tons, 57% ash (105 million tons) was used and remaining 79 million tons was disposed off on open land.

- By 2030, ash generation may touch 600 million tons; *120 million tons would be coal bottom ash*.



ENVIS Centre on Flyash, Ministry of Environment, Forests & GOI (2016)



Utilization of Fly Ash in India

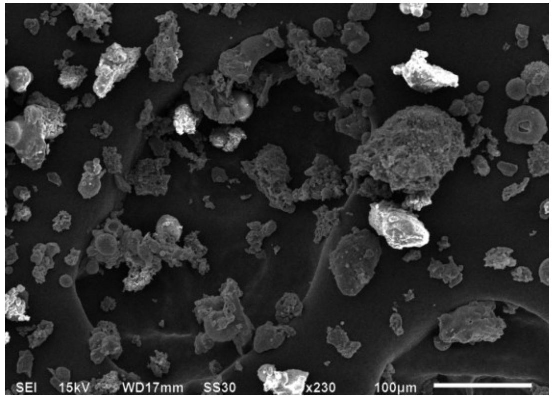
Possible Uses of Coal Bottom Ash

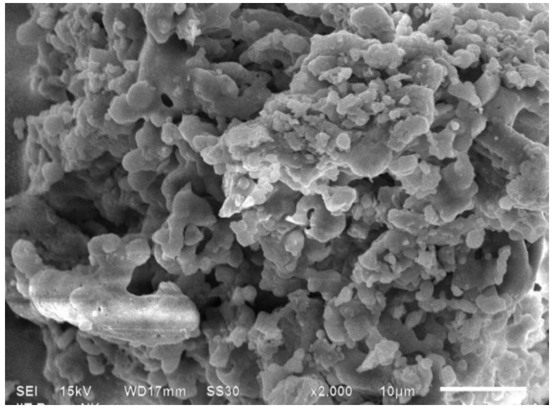
- Used as sand replacement in concrete
- Coal bottom ash is predominantly used for the following applications:-
  - Road base and sub-base
  - Structural fill
  - Backfill
  - Drainage media
  - Aggregate for concrete, asphalt and masonry
  - Abrasives/traction
  - Manufactured soil products

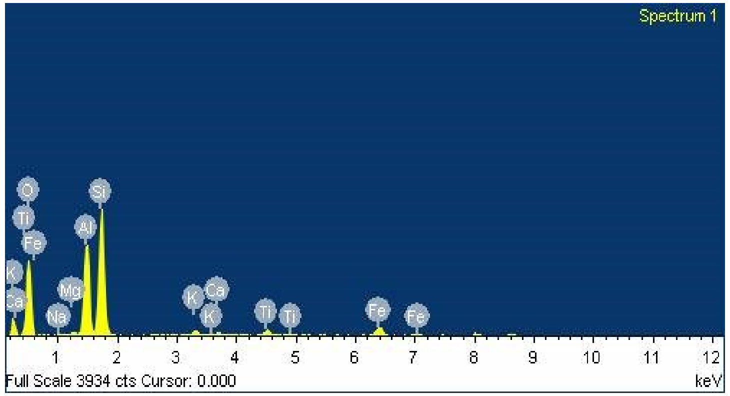
Properties of Coal Bottom Ash

Property	Value
Specific gravity	1.30-2.47
Water absorption (%)	5.50- 31.58
Fineness Modulus	1.37-2.80

Composition	Value(%)
Silica Oxide	41.7- 61.9
Alumina Oxide	17.1-29.2
Iron Oxide	6.5-8.5
Calcium Oxide	0.7-22.5
Magnesium Oxide	0.3-4.9
Sodium Oxide	0.08-1.4



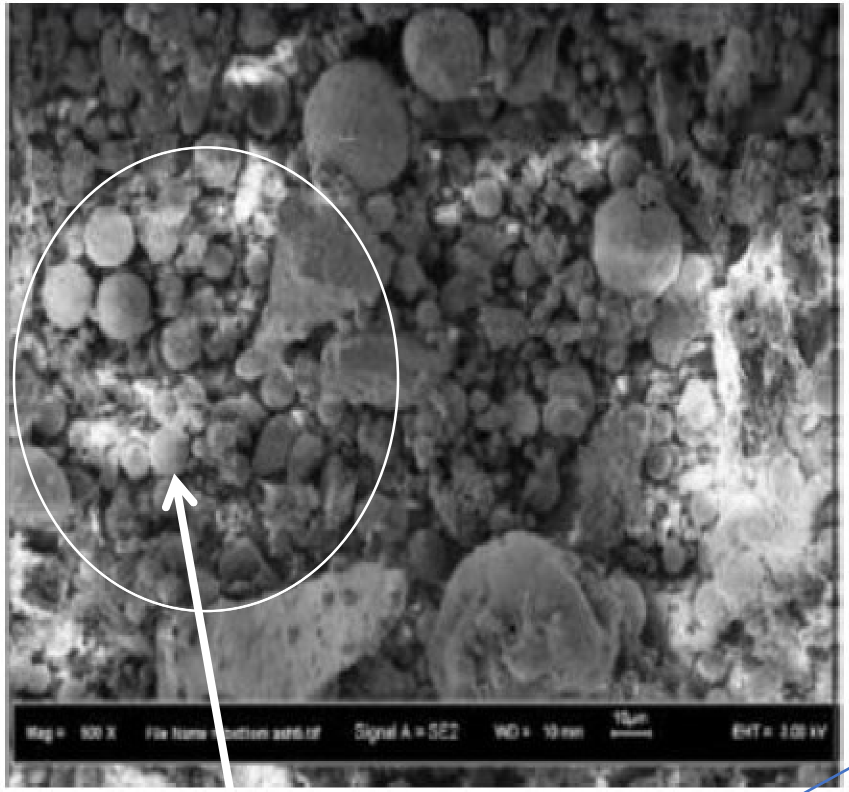


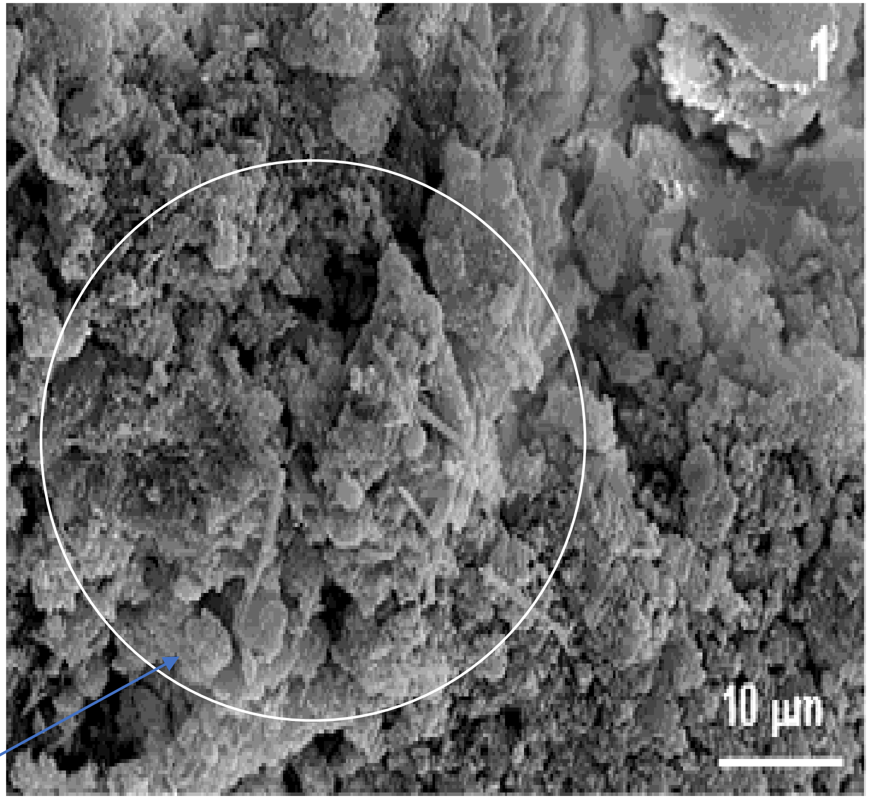


SiO2 = 60.33%; Al2O2 = 19.46 %;
Fe2O3 = 11.78%;
CaO = 0.62% **MgO** = 0.26 %;
Na2O = 0.40%;
K2O = 0.88%; **SO3** = 0.24 %;
LOI = 1.00%

- Particles are angular, irregular, porous and have rough surface texture.
- Range from fine sand to gravel.
- Porous particles absorb water internally during mixing process.
- Pop corn type particles are easily degradable

SEM Analysis of Bottom Ash





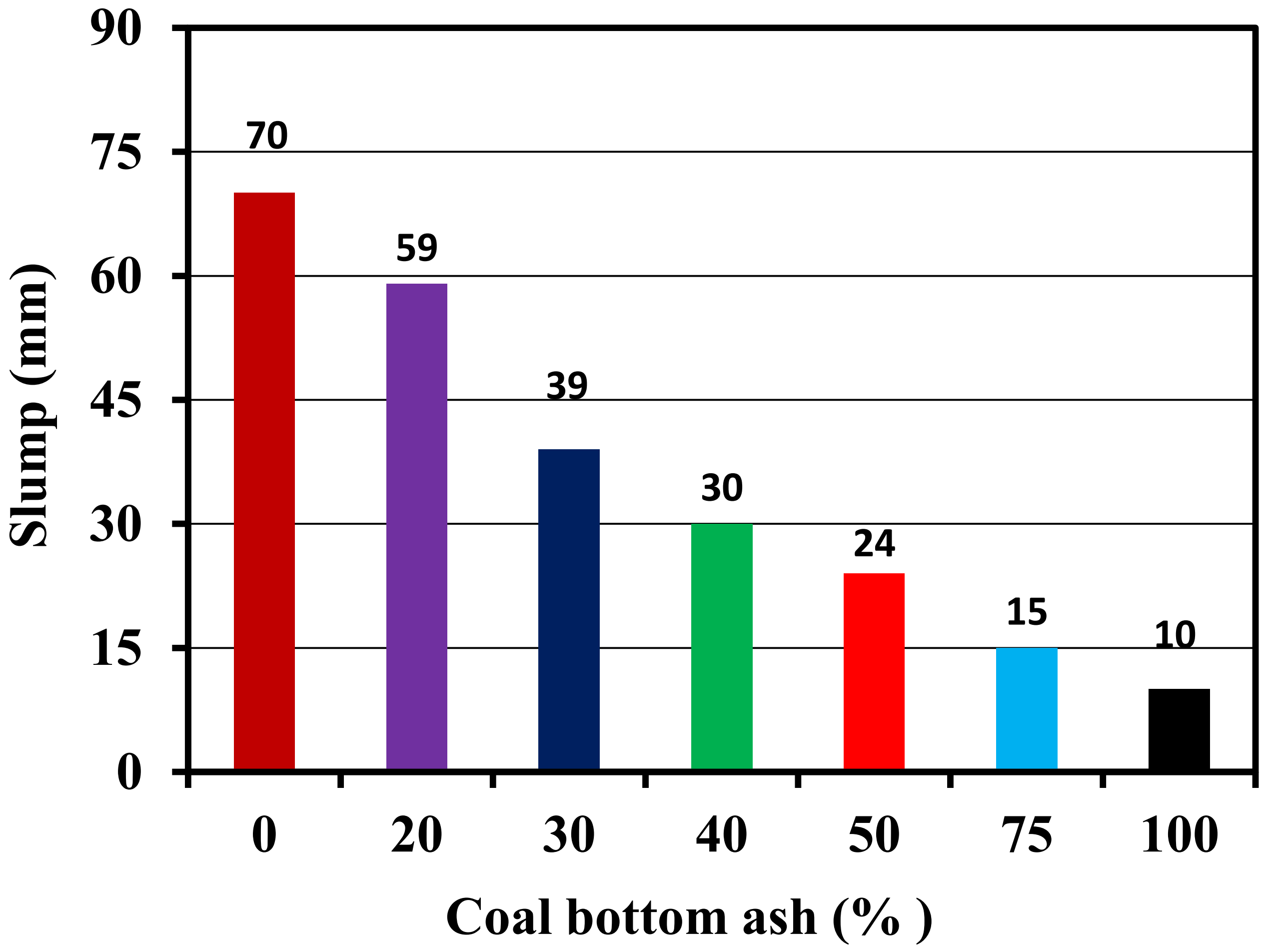
Round to irregular shape of bottom ash particle

Muhardi et al. (2010), Electronic Journal of Geotechnical Engineering, 15, 1117-1129

Fernadez-Turiel et al. (2004), Energy & Fuels, 18, 1512-1518

Properties of concrete made with coal bottom ash

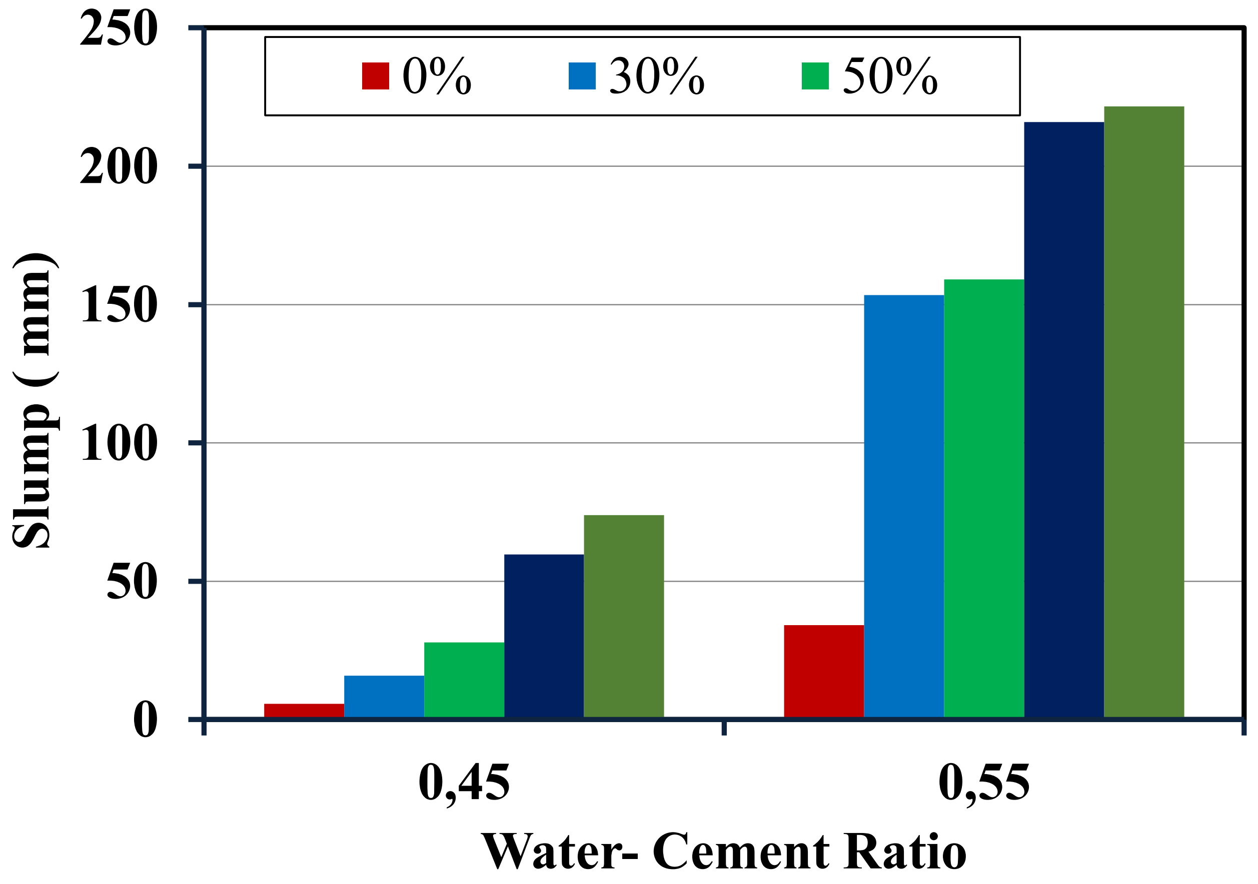
Slump



- *Control Mix 1:1: 2.43; (Cement = 479 kg/m^3 ; W/C = 0.45; Sand = Grade III)*
- **During mixing process, part of water added absorbed by the porous particles of CBA. Net quantity of water for lubrication reduced**
- **Inter-particle friction increased due to rough texture of CBA particles**

Singh and Siddique (2014) Construction and Building Materials, 50, 246-256

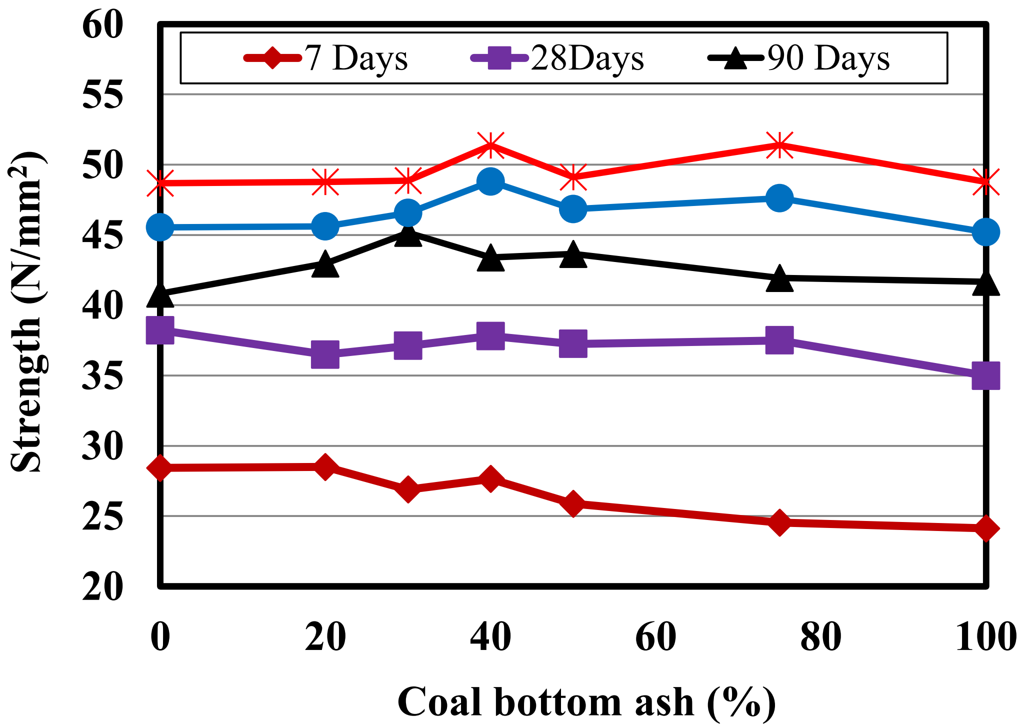
Slump



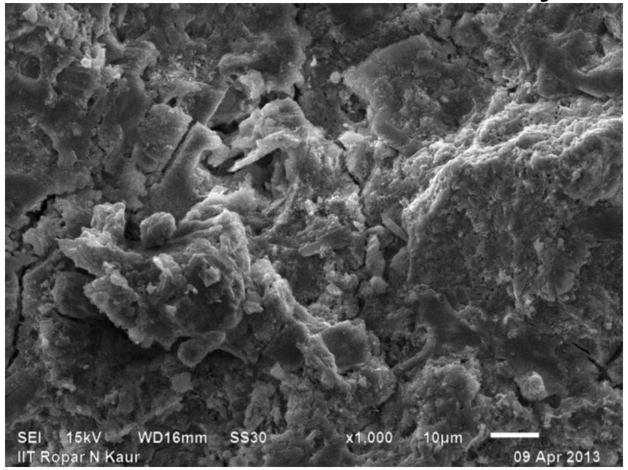
- *Control Mix: 1 : 1.74 : 3.48; Cement: 382 kg/m^3 ; W/C: 0.45 and 0.55*
- **Slump increased with increase in CBA content**
- **Ball bearing effect of Spherical particle shape of CBA caused increase in slump**

Bai et al (2005), Construction and Building Materials, 19, 691-697

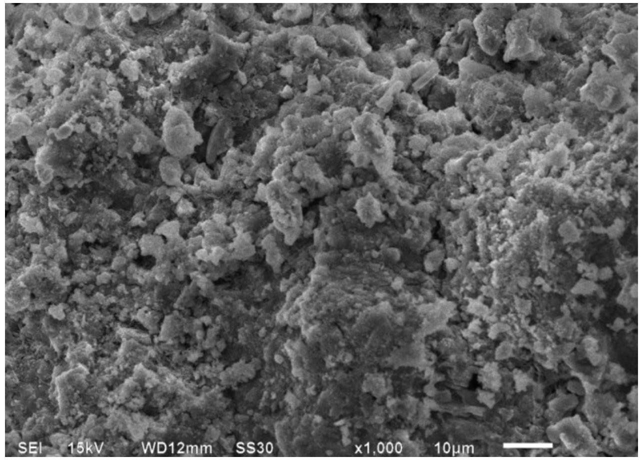
Compressive strength



Control concrete – 28 days



100 % BA concrete – 28 days

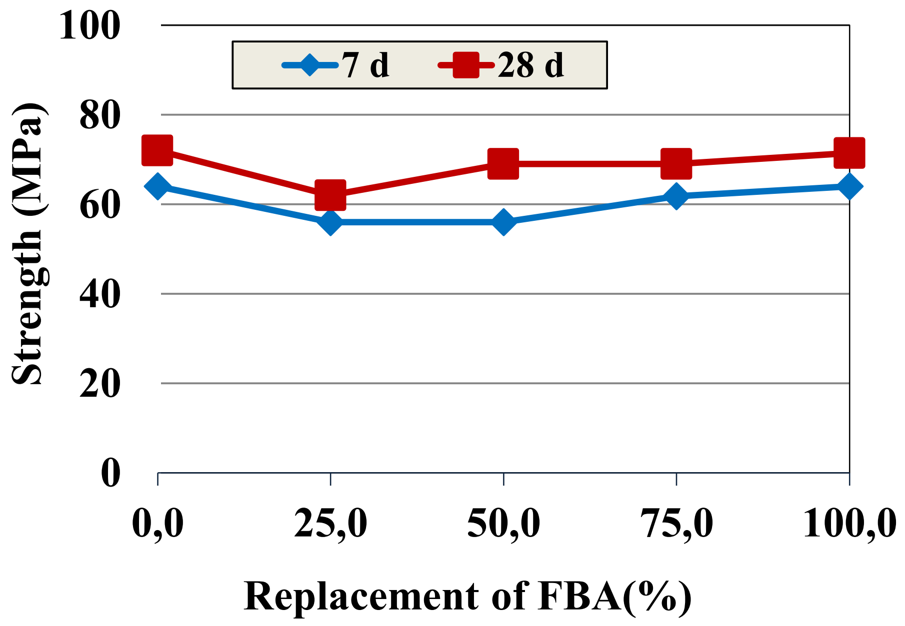


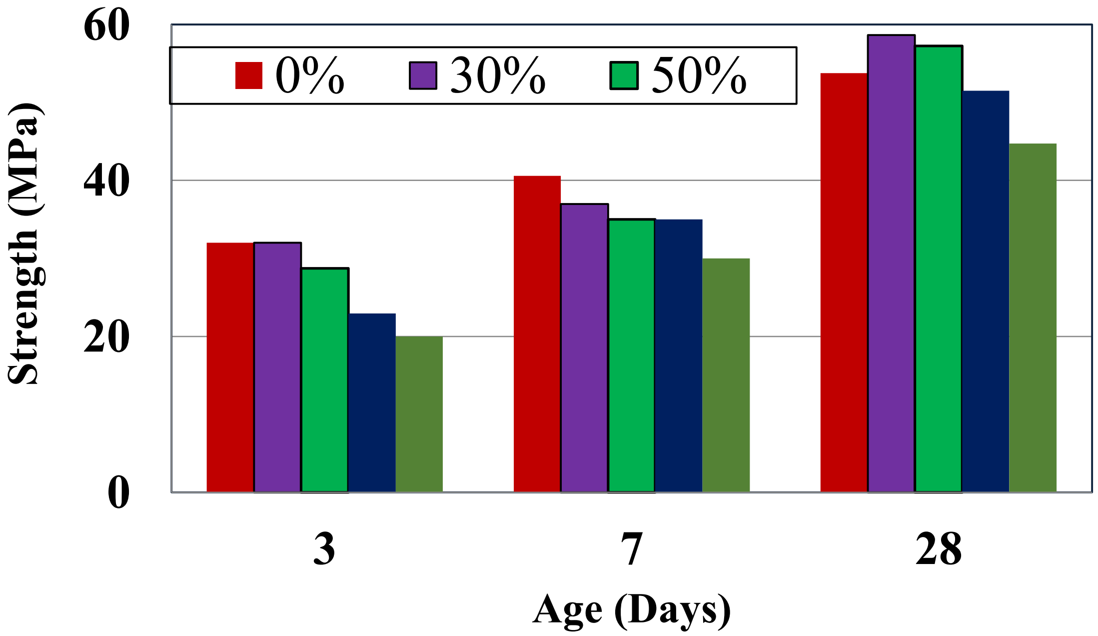
- *Control Mix 1 : 1 : 2.43; Cement = 479 kg/m^3 ; W/C = 0.45; Sand = Grade III*
- CSH gel is more compact and finely spread in control concrete.
- Comparatively voids in bottom ash concrete mixture are more.

- *Control Mix 1 : 1 : 2.43; Cement = 479 kg/m^3 W/C = 0.45; Sand = Grade III*
- At 28 day, 50 and 100 BAC achieved 98.47 % and 91.55% CS of control concrete
-

Singh and Siddique (2014) Construction and Building Materials, 50, 246-256

Compressive strength





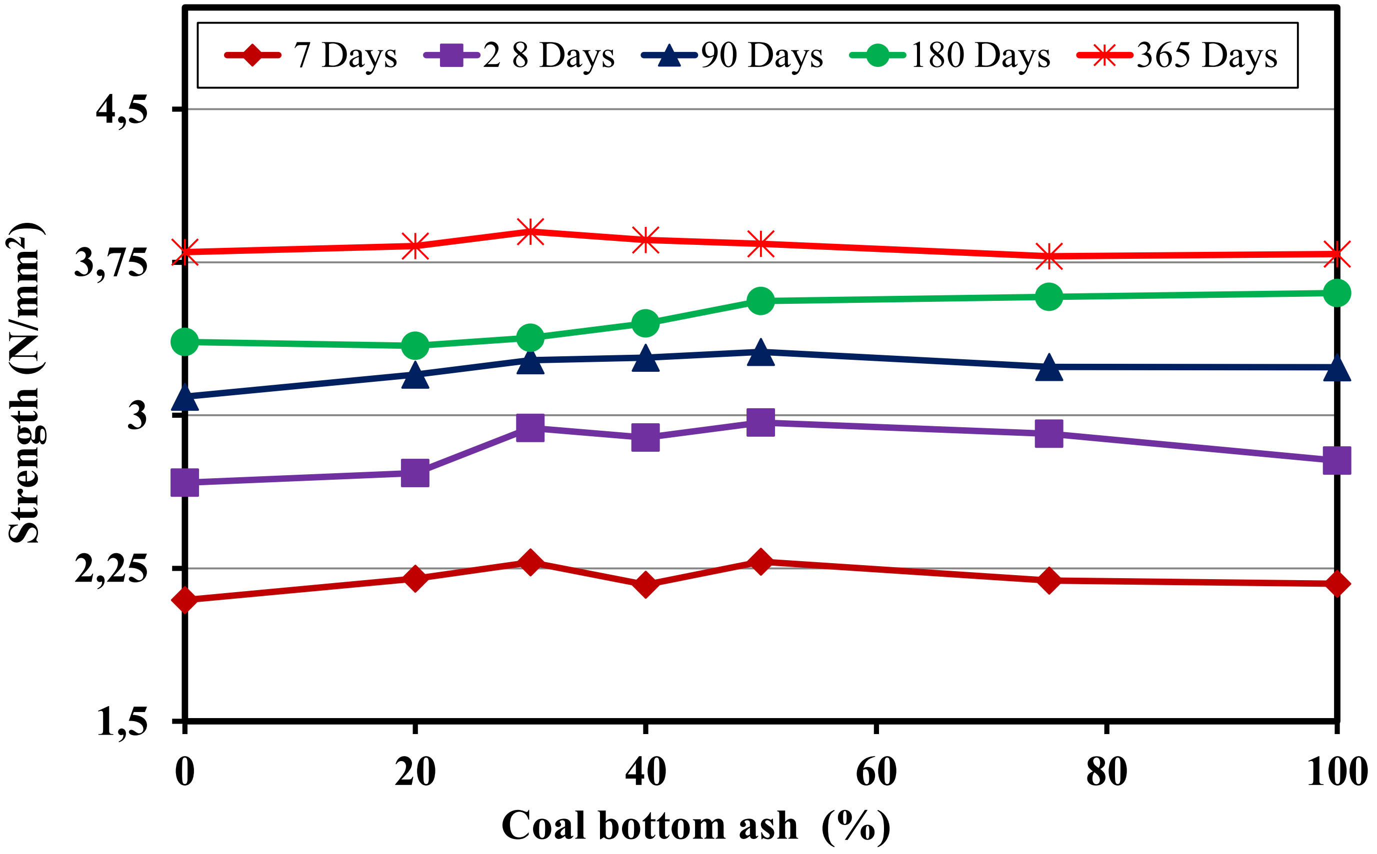
Control Mix 1 :0.72 : 1.36; Cement = 607 kg/m^3 ; BFS= 186 kg/m^3 ; SF = 143 kg/m^3 SP = 2.5%

- ***Control Mix 1 : 1.74 : 3.48; Cement = 382 kg/m^3 ; W/C = 0.45***
- **At 28 days, concrete mix containing 30% and & 50% displayed higher compressive strength.**

Kim and Lee (2011) Construction and Building Materials, 25, 1115-1122

Bai et al. (2005), Construction and Building Materials, 19, 691-697

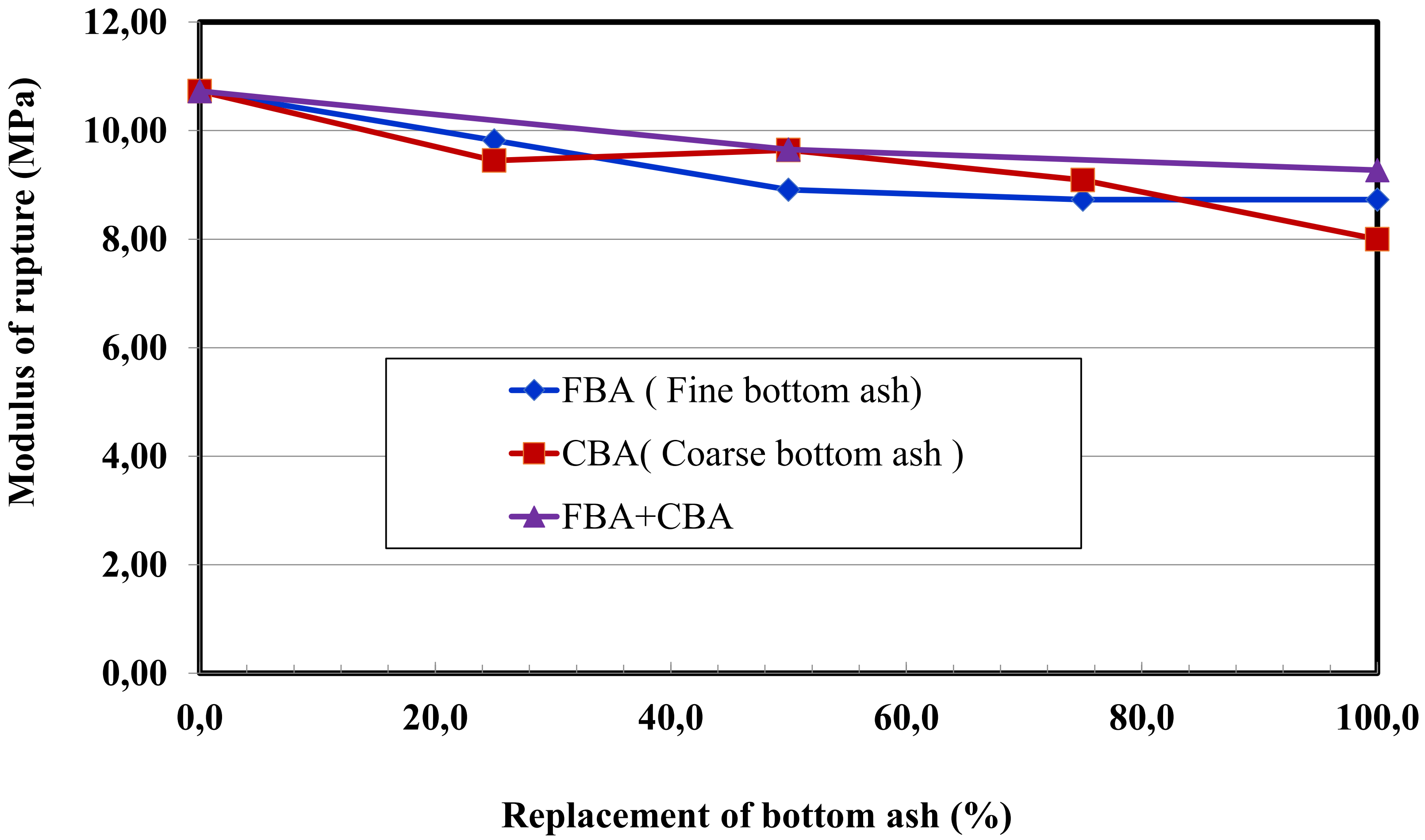
Splitting Tensile Strength



- ***Control Mix 1 : 1 : 2.43; Cement = 479 kg/m³ ; W/C = 0.45; Sand = Grade III***
- **At 28 day, 50 and 100 BAC achieved 111% and 104% strength of control concrete**
- **At 90 day, 50 and 100 BAC achieved 107% and 104.6% strength of control concrete**

Singh and Siddique (2014) Construction and Building Materials, 50, 246-256

Flexural Strength

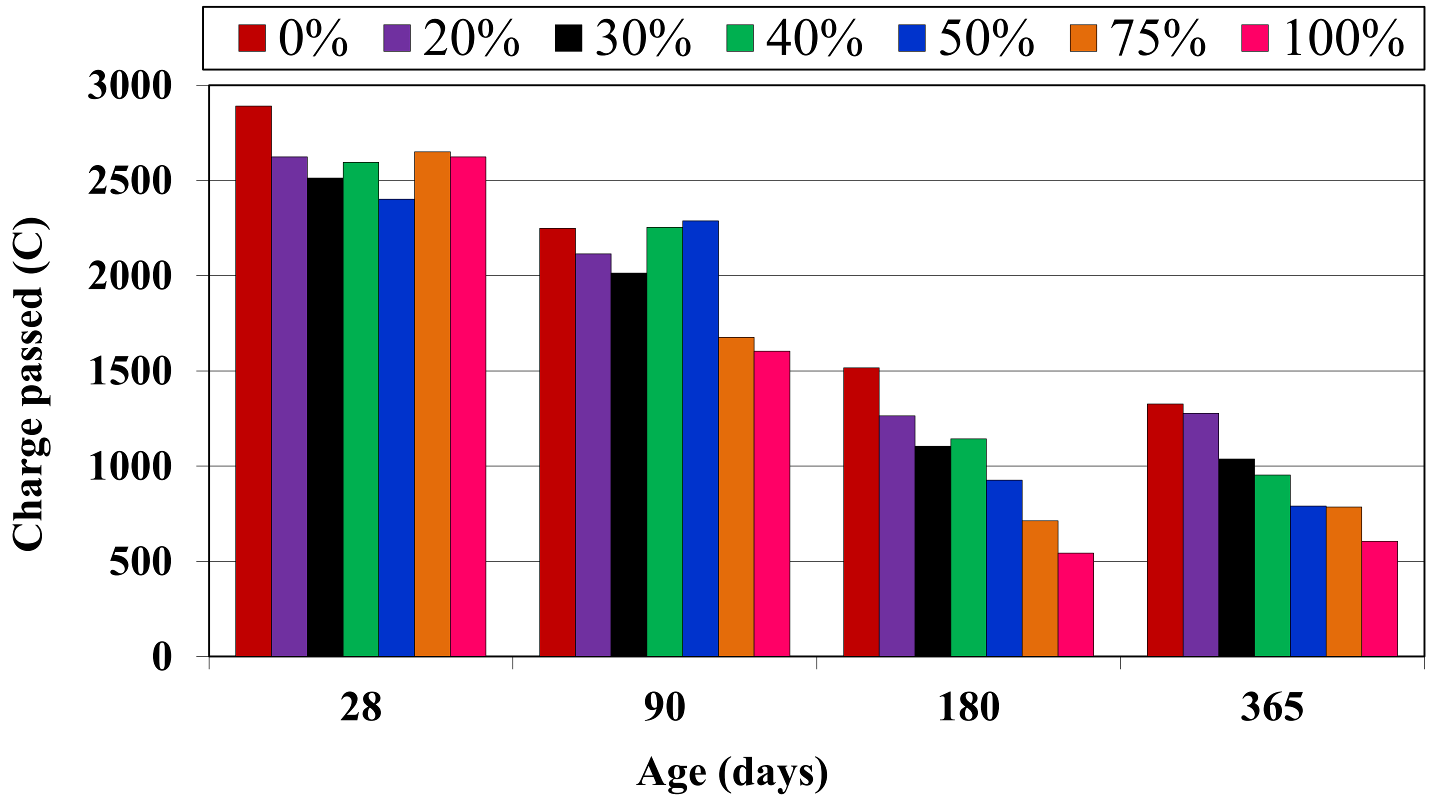


Control Mix 1 :0.72 : 1.36; Cement = 607 kg/m³ ; BFS= 186 kg/m³ ; SF = 143 kg/m³ SP = 2.5%

- *Flexural strength decreased with use of FBA as fine aggregate; CBA as CA and Both FBA and CBA*

Kim and Lee (2011) *Construction and Building Materials; 25:1115-1122*

Rapid Chloride Permeability

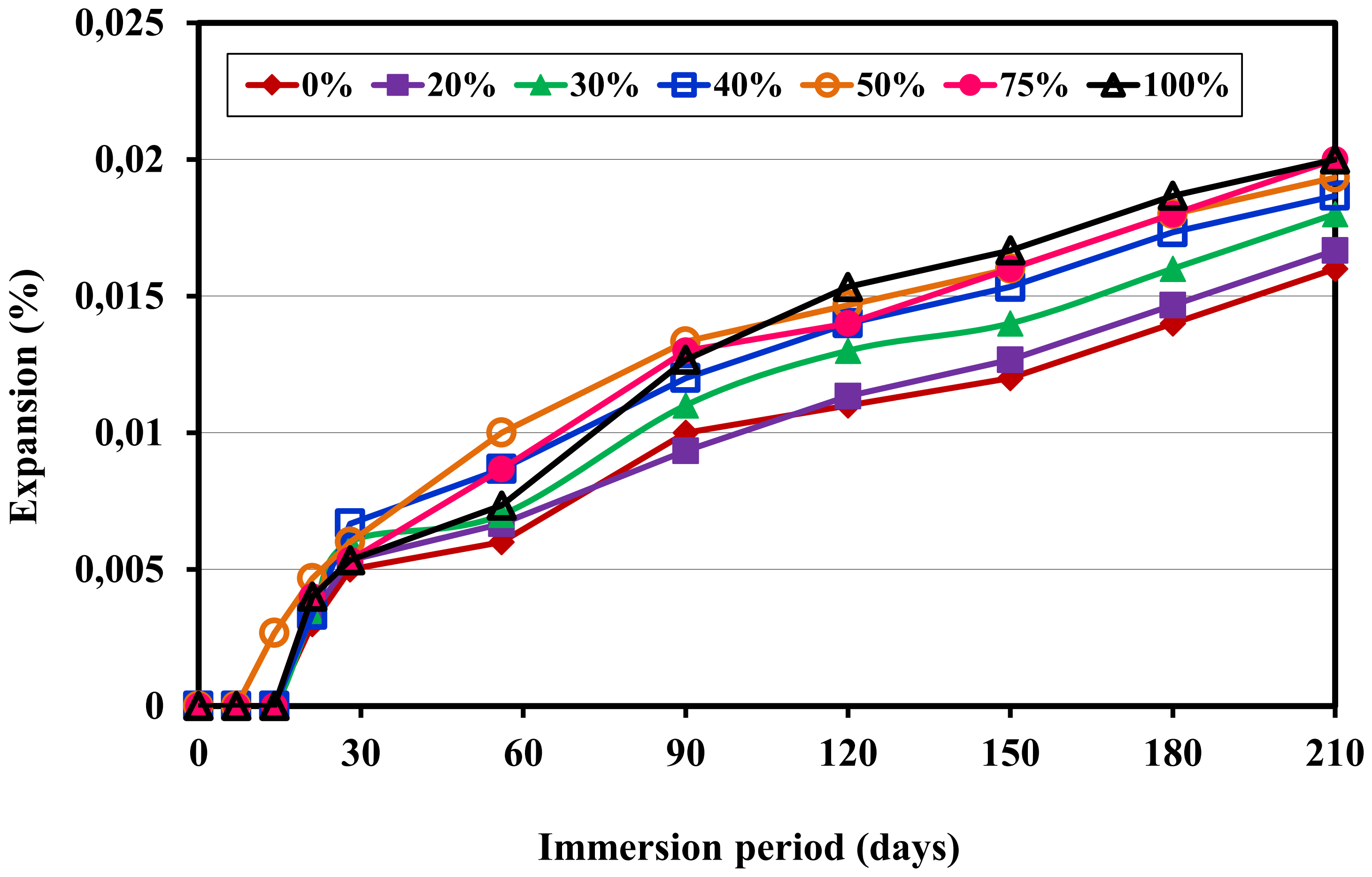


ASTM C1202	
> 4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 – 1000	Very Low
< 100	Negligible

- *Control Mix 1 : 1 : 2.43; Cement = 479 kg/m³ ; W/C = 0.45; Sand = Grade III*

Singh and Siddique (2014) Construction and Building Materials, 68, 39-48

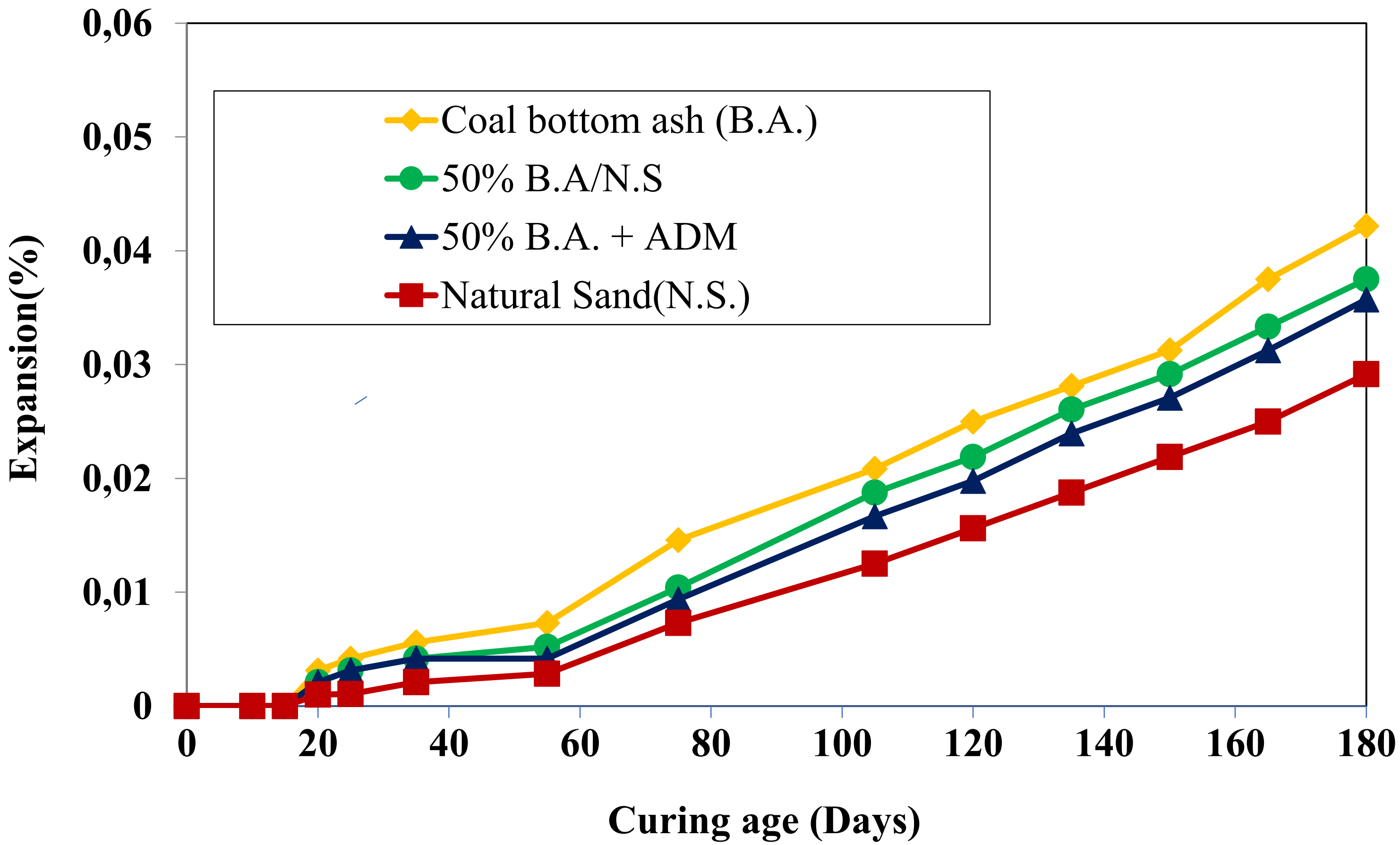
Resistance to Sulfate Attack



- ***Control Mix 1 : 1 : 2.43; Cement = 479 kg/m^3 ; W/C = 0.45; Sand = Grade III***
- **BA concrete (BAC) experienced almost equal expansion under sulfate attack.**
- **Loss in compressive strength of cement mortars start at 0.1 % expansion**

Singh and Siddique (2014) Construction and Building Materials, 68, 39-48

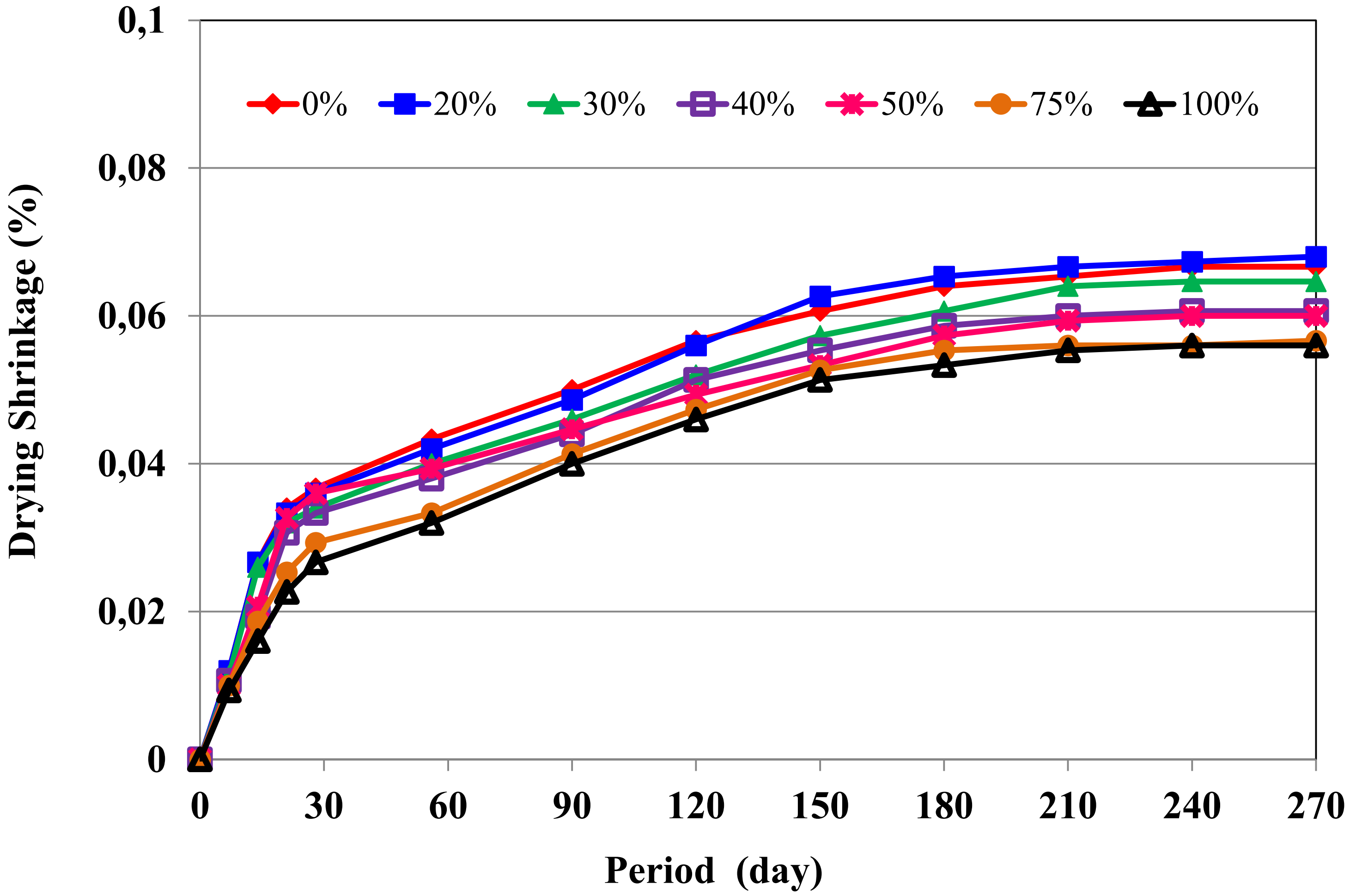
Resistance to Sulfate Attack



- *Control Mix 1 : 2.63 : 2.39; Cement = 356 kg/m^3 ; Slump = 100 mm*
- **Expansion strains increased on use of CBA.**
- **Expansion strains reduced on use of water reducing admixtures.**
- **Expansion displayed by bottom ash concrete mix after 180 days was 0.035%**

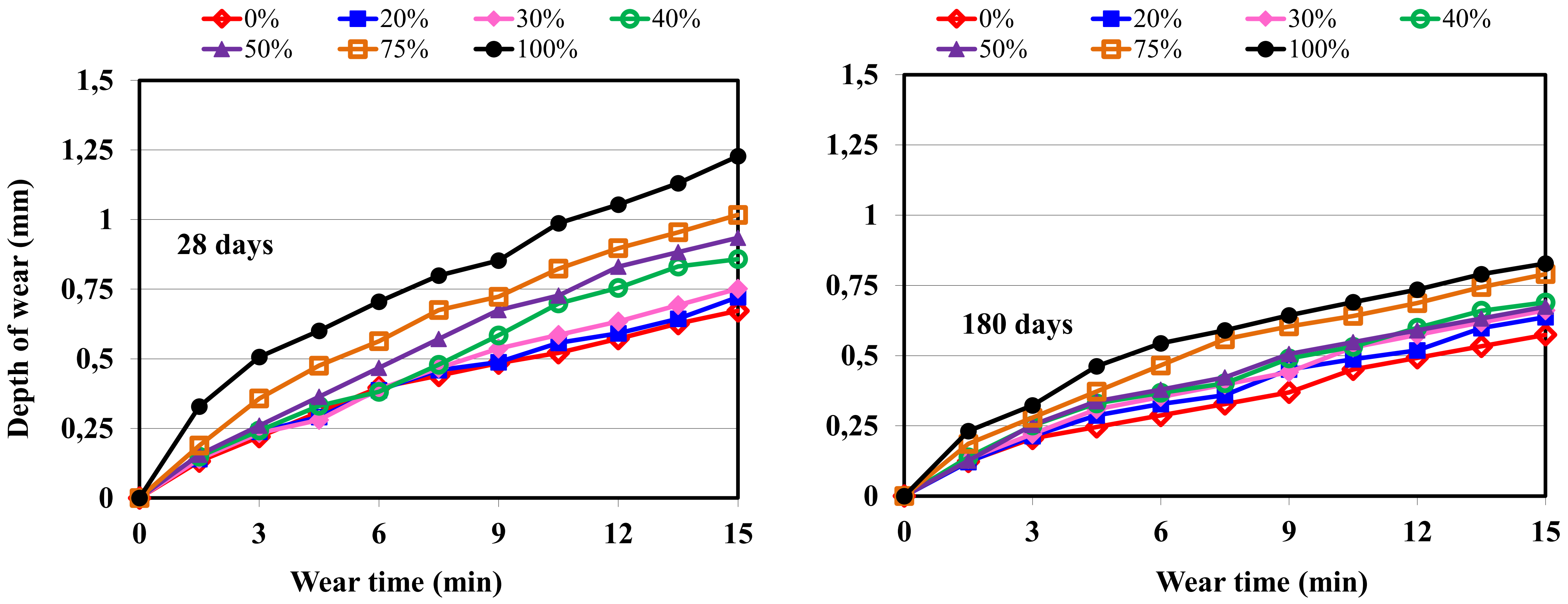
Ghafoori and Bucholc (1997), ACI Materials Journal, 94 (2), 90-101

Drying Shrinkage



- Drying shrinkage decreased with increase in CBA content. CBA particles released internally absorbed water during drying process.
- At 270 days, shrinkage strains of BAC mixtures varied between 680 x 10-6 and 560 x 10^{-6} as compared to 666.67 x 10^{-6} of control concrete.
- Bottom ash concrete (BC) exhibits better dimensional stability.

Abrasion Resistance



- *At 28 days, depth of wear for* BAC mixes *was* higher than control concrete.
- At 180 days, at 15 min wear, depth of wear reduced from 1.23 to 0.83 mm for 100 BAC
- Depth of wear after 7.5 min wear time was much less than that specified for heavy duty tiles in BIS 1237 -2010, (2mm)

Conclusions

- Strength development pattern of bottom ash concrete is similar to that of conventional concrete but there is decrease in strength at all the curing ages
- Decrease in strength of concrete is mainly due to higher porosity and higher water demand on use of bottom ash in concrete
- Compressive strength and tensile strength can be improved by reducing the water demand by using chemical admixtures
- Acts a potential viable material to be used as fine aggregate & helps in reduction of quarry mining and land-filling

Waste Foundry Sand

Also known as

- Spent foundry sand (SFS)
- Used foundry sand (UFS)

Waste Foundry Sand

- The metal casting industry generates spent/waste foundry sands. Foundries use new, virgin sand to make casting molds. These sands are high quality silica sand which form the outer surface of the mold.

- In the casting process, molding sands are recycled and reused multiple times.

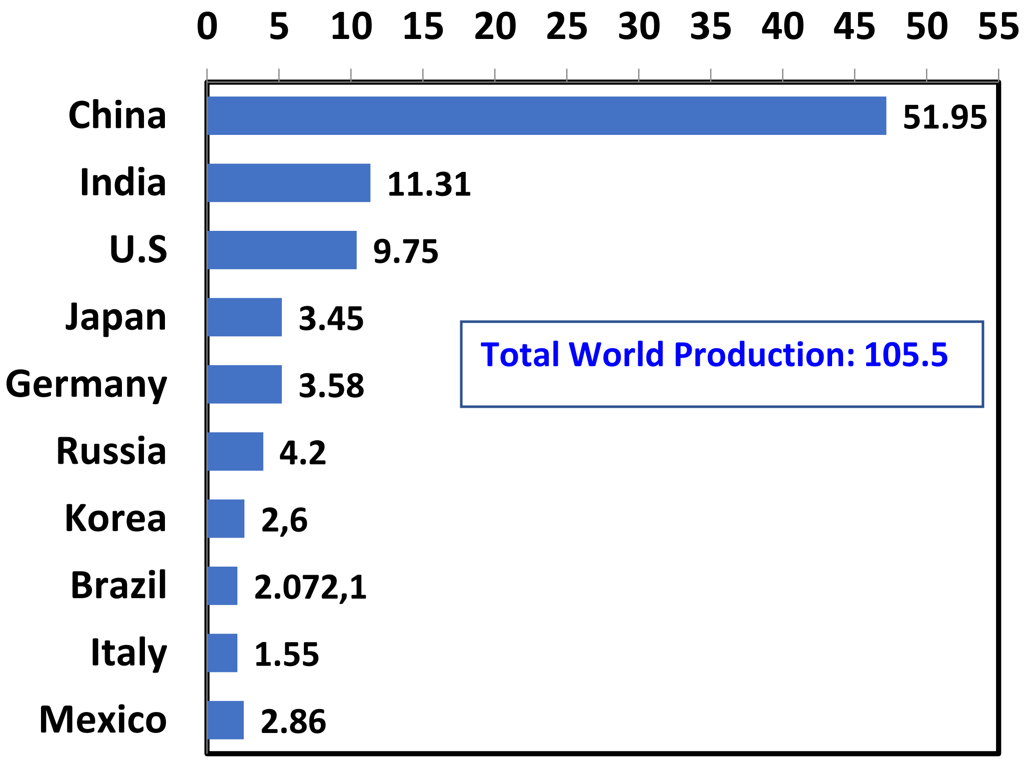
- When it is not possible to further reuse in the foundry, it is removed from the foundry and is termed as <u>waste foundry sand</u>.

Waste Foundry Sand

Waste & Fresh Foundry Sand

Production of Waste Foundry Sand

- About 35,000 foundries in the world with annual production of 105.5 million tonnes.
- China has largest foundries (9374), followed by India (6000)
- The share of Iron foundries is the maximum i.e. almost 56%, followed by steel with 14% and non-ferrous ones 30%.
- Utilization of Waste Foundry Sand, is an unexplored area



Casting production worldwide in 2020 (Million Tons)

(https://www.statista.com/statistics/)

Types of Foundry Sand

Classification of foundry sand depends upon the type of binder system. Two type of binder system are used and on the basis of this, foundry sand are categorized as:

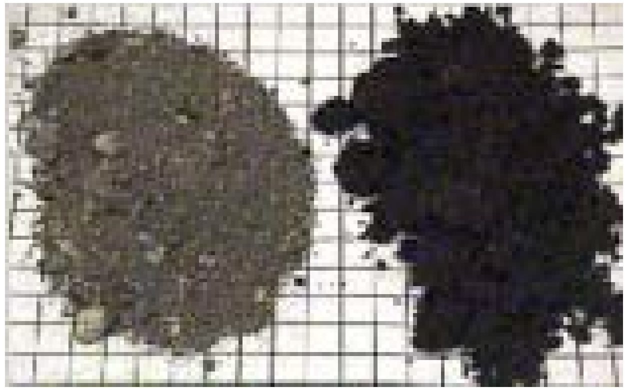
- **Green Sand** (Clay bonded sand)

  Carbonaceous additives : 2 - 10%

  Bentonite clay : 4 - 10%

  Silica sand : 85 - 95%

  Water : 2 - 5%



- **Chemically bonded sand**

  Chemical binder : 1 - 3%

  Silica : 93 - 99%

Physical Properties of WFS

- Shape: Sub- angular to round in shape
- Color: green sand – black
  chemically bonded sand – off white
- Size: 85- 95% material ranges (0.6 - 0.15 mm)
  5- 12% material is smaller than 0.075 mm

Properties	Javed and Lovell (1994)	Naik et al. (2001)	Guney et al. (2010)	Siddique et al. (2011)
Specific gravity	2.39-2.55	2.79	2.45	2.61
Fineness modulus	-	2.32	-	1.78
Unit Weight (kg/m^3)	-	1784	-	1638
Absorption (%)	0.45	5.0	-	1.3
Moisture content (%)	0.1-10.1	-	3.25	-
Clay lumps and friable particles	1- 44	0.4	-	0.9
Materials finer than 75µm (%)	-	1.08	24	18

Chemical Composition of WFS

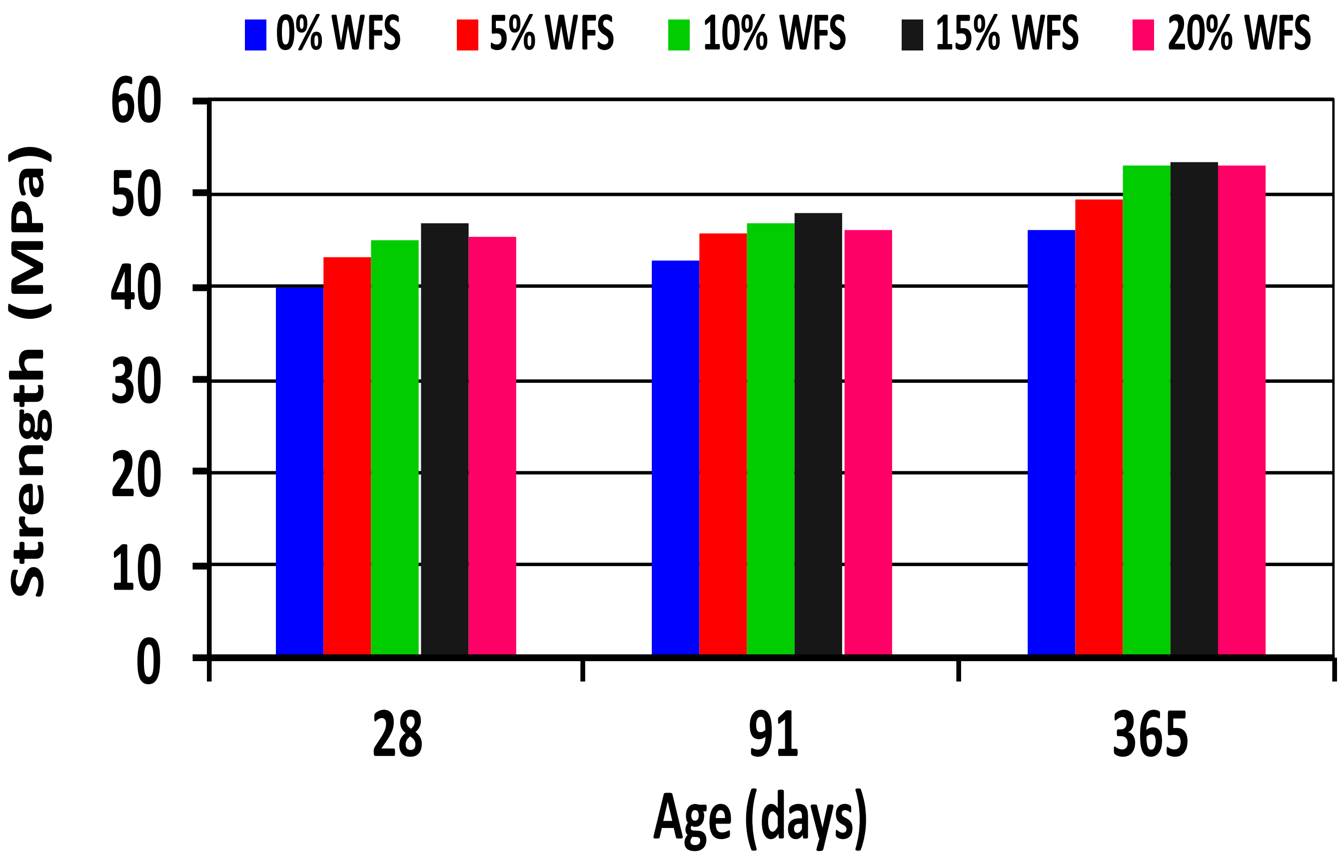
- Depends on the type of metal molded at the foundry, type of binder, and combustible used
- Consists primarily of silica sand, coated with a thin film of burnt carbon, residual binder (bentonite, sea coal, resins/chemicals) and dust
- Hydrophilic and consequently attracts water to its surface
- Depending on the binder and type of metal cast, the pH can vary between 4 and 8

Constituents	Values (%)			
	American Foundrymen's Society (1991)	Guney et al. (2010)	Etxeberria et al. (2010)	Siddique et al. (2011)
SiO_2	87.91	98	95.10	78.81
Al_2O_3	4.70	0.8	1.47	6.32
Fe_2O_3	0.94	0.25	0.49	4.83
CaO	0.14	0.035	0.19	1.88
MgO	0.30	0.023	0.19	1.95
SO_3	0.09	0.01	0.03	0.05
Na_2O	0.19	0.04	0.26	0.10
K_2O	0.25	0.04	0.68	-
TiO_2	0.15	-	0.04	-
Mn_2O_3	0.02	-	-	-

Applications of Foundry Sand

- In Portland Cement Concrete
- In Flowable Fills In Embankments
- In Roadway Construction
- In Barrier Layer Construction
- As Soil Reinforcement
- In Hot Mix Asphalt

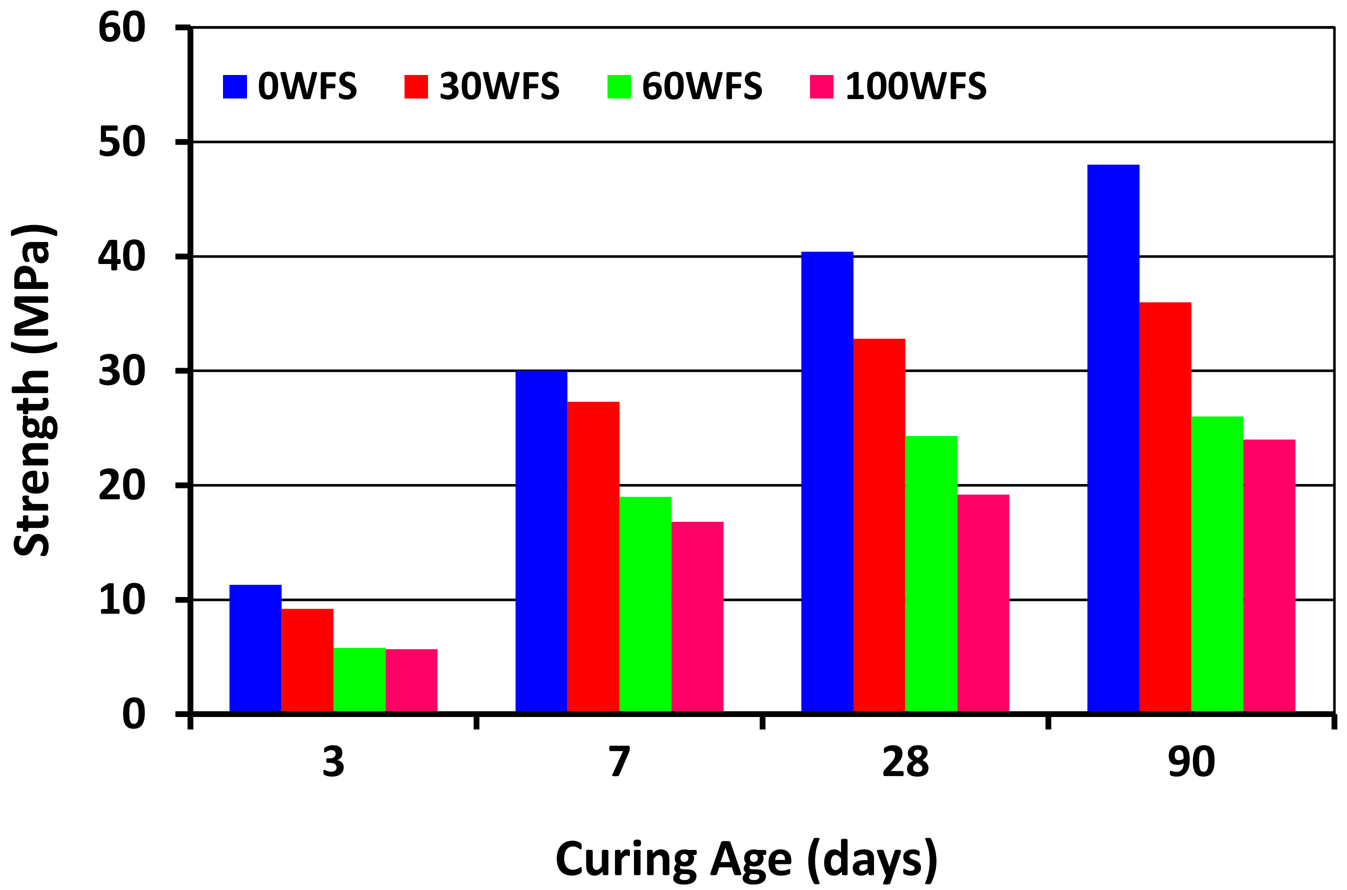
Compressive Strength



- *Control mix proportion 1:1.23:2.53 (Cement 450 kg/m^3; w/c 0.42)*
- **Concrete mixes made with WFS exhibited higher strength.**
- **15% WFS exhibited higher strength**
- **28-day strength increased by 8.3, 12.3, 17 and 13.5% with increase in WFS content**

Singh and Siddique (2012) Construction and Building Materials, 28, 421-426

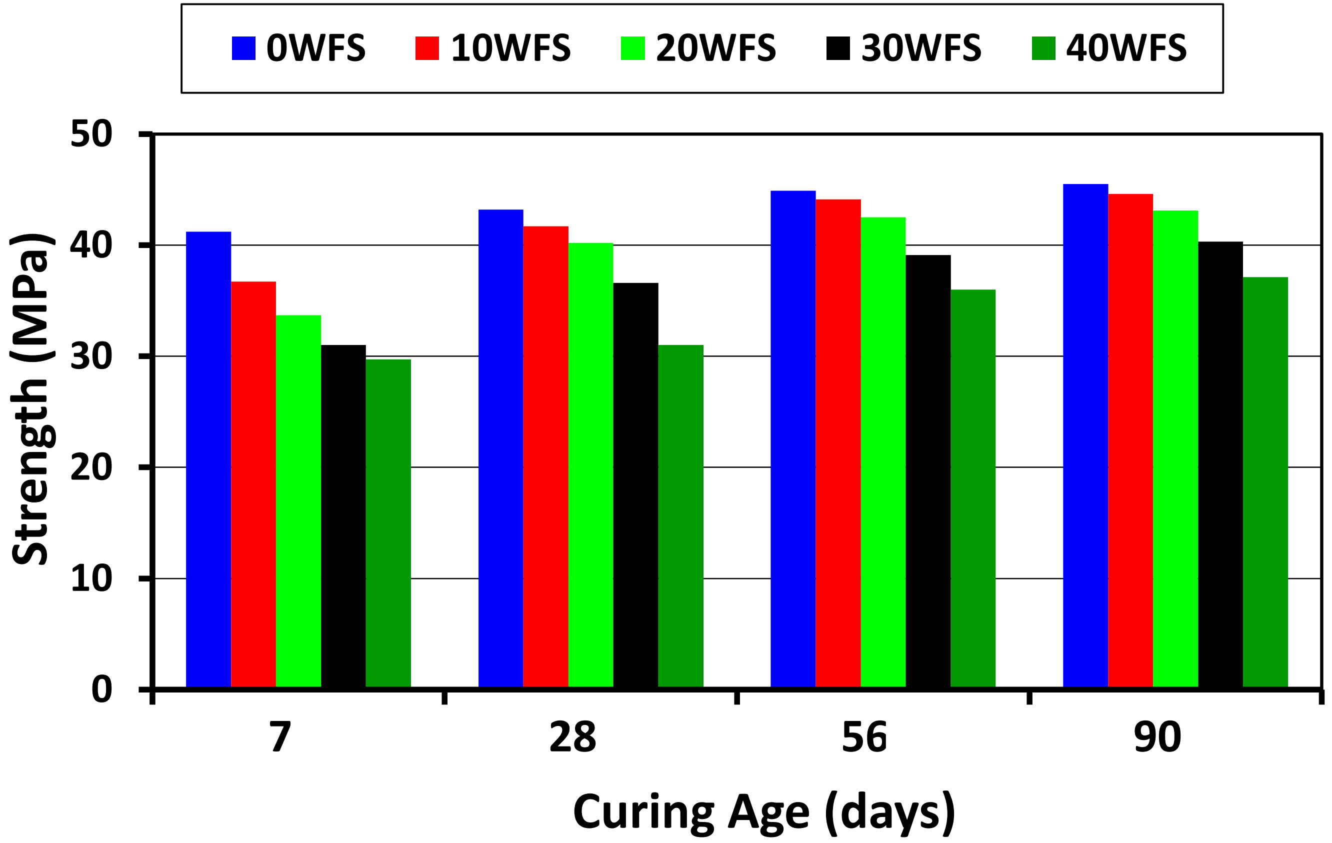
Compressive Strength



- *Control mix = 1:1.73:3.57 (Cement 350 kg/m^3; w/c 0.5)*
- With increase in WFS content, strength decreased
- 30% Fine aggregate replacement with WFS gives acceptable strength values
- Decreased strength → increased surface area → weakened the interfacial zone between WFS and Cement paste → increased the pore size

Khatib et al. (2013) Construction and Building Materials, 47, 867-871

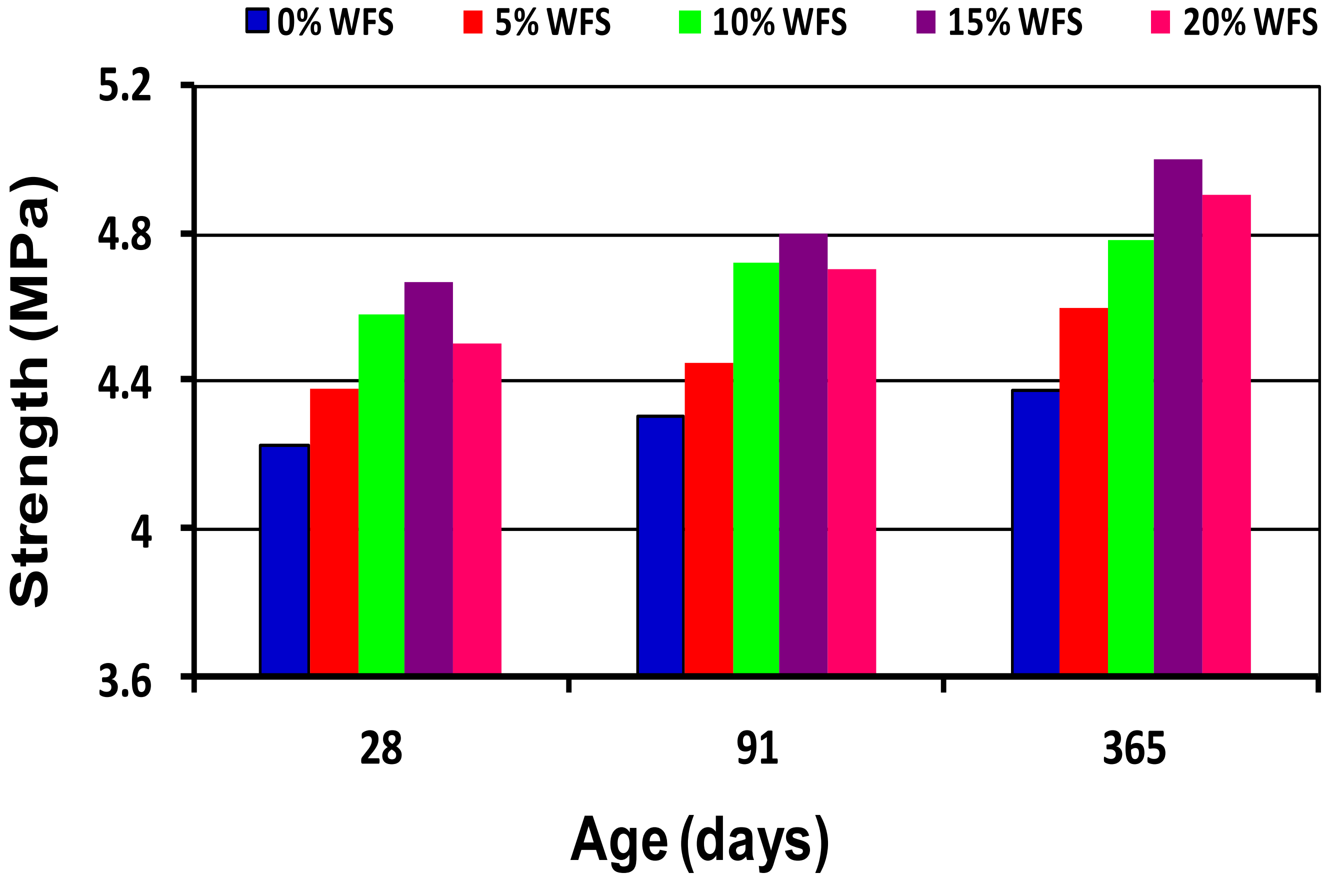
Compressive Strength



- *Control mix proportion 1:1.26:2.87 (Cement 350 kg/m³; w/c 0.45)*
- At 28 days, compressive strength of 0%WFS = 43.2 MPa; In other mixes decreased in strength was observed
- Addition of WFS decreased the strength at all ages, due to -- High surface area – low water cement gel in matrix – low binding – loose contact

Basar and Aksoy (2012) Construction and Building Materials, 35, 508-515

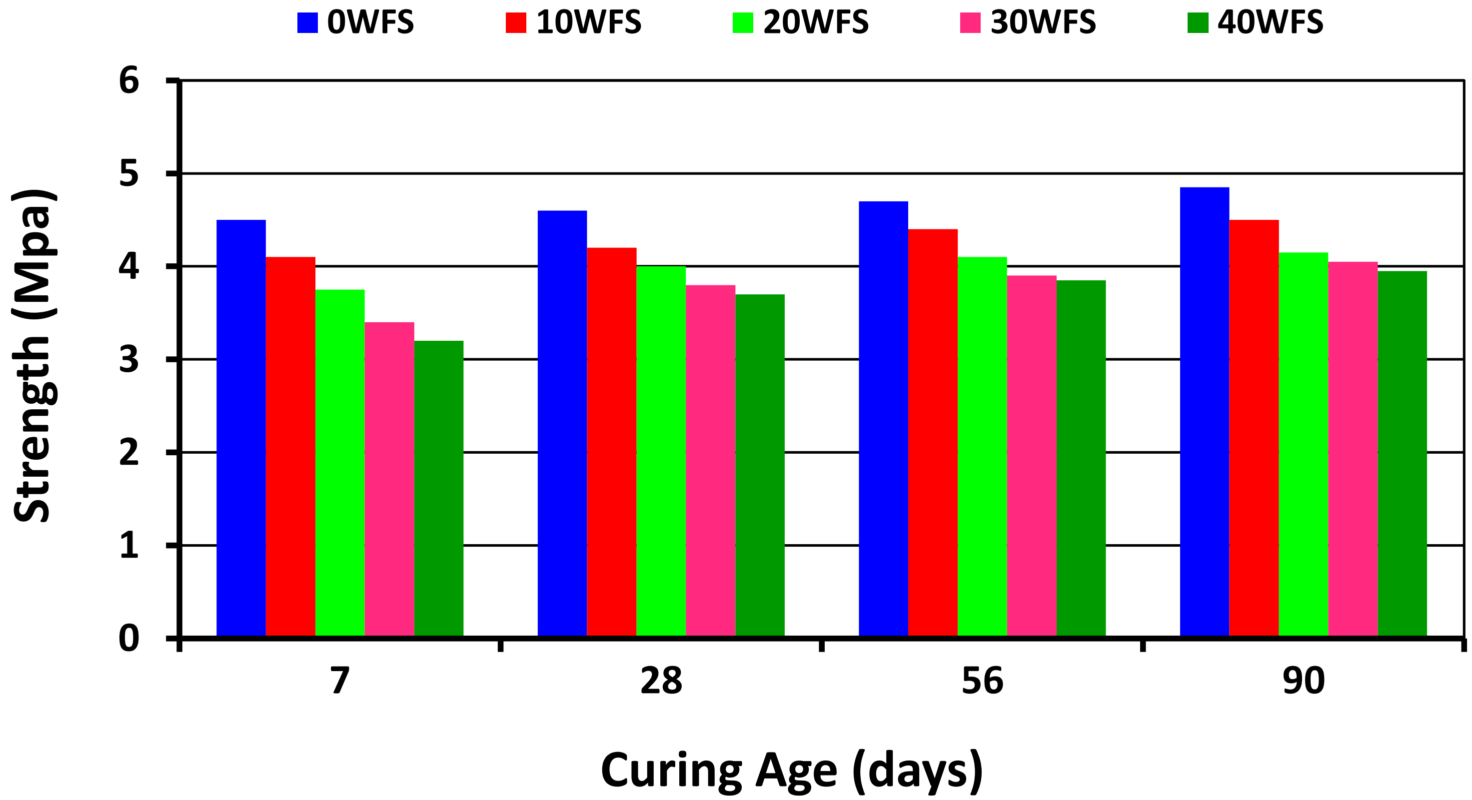
Splitting Tensile Strength



- ***Control mix proportion 1:1.23:2.53 (Cement 450 kg/m^3; w/c 0.42)***
- **Strength of all concrete mixes increased with age (7 to 365 days)**
- **28-day strength of increased by 3.55, 8.27, 10.40 and 6.38%**
- **365 day strength increased by 5.1, 9.1, 14.1 and 11.85%**

Singh and Siddique (2012) Construction and Building Materials, 28, 421-426

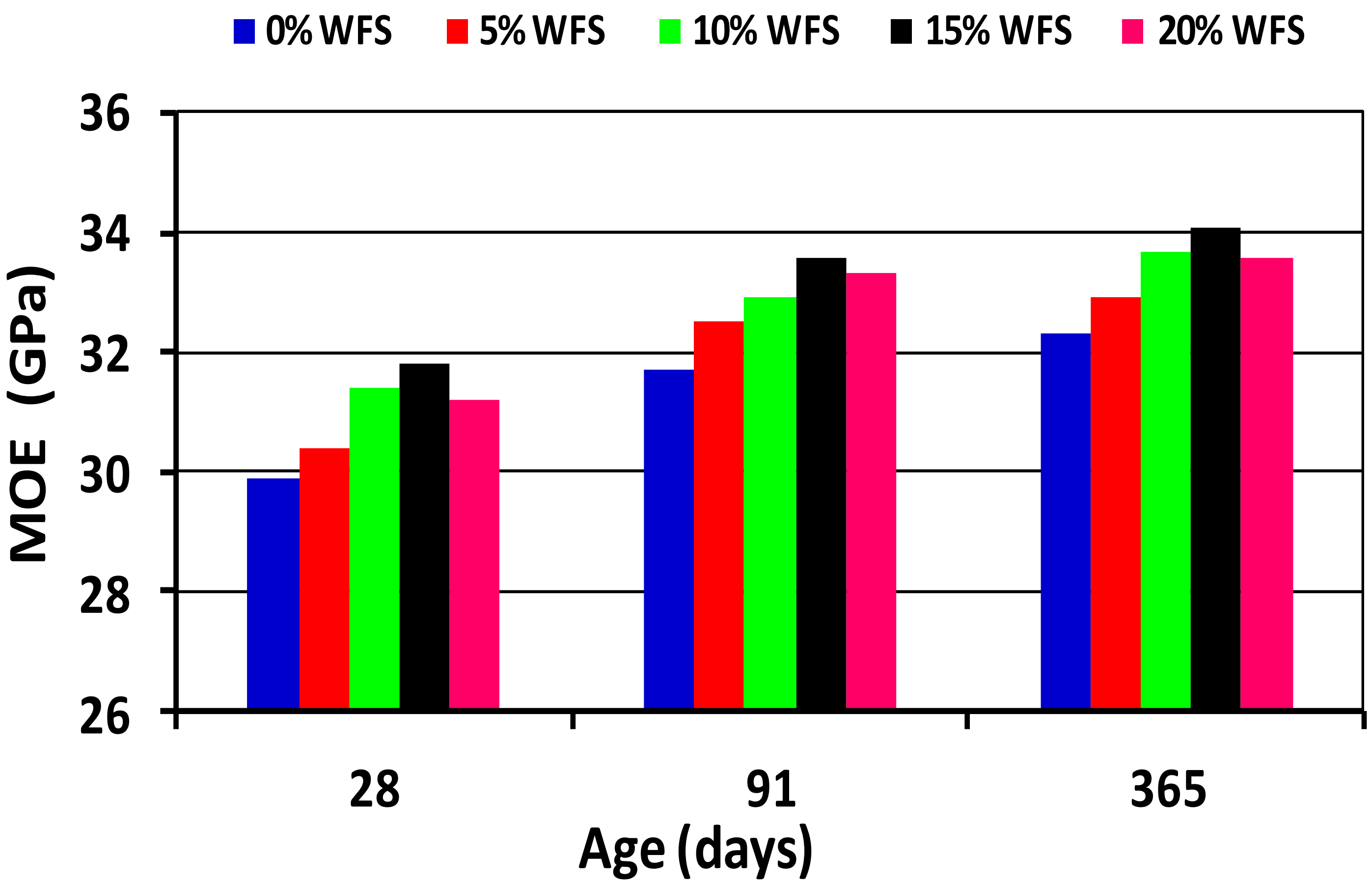
Splitting Tensile Strength



- *Control mix proportion 1:1.26:2.87 (Cement 350 kg/m^3; w/c 0.45)*
- **With increasing WFS content as replacement to fine aggregate decrease in tensile strength was observed**
- **At all ages, tensile strength of WFS + concrete mixes decreases compared to control**

Basar and Aksoy (2012) Construction and Building Materials, 35, 508-515

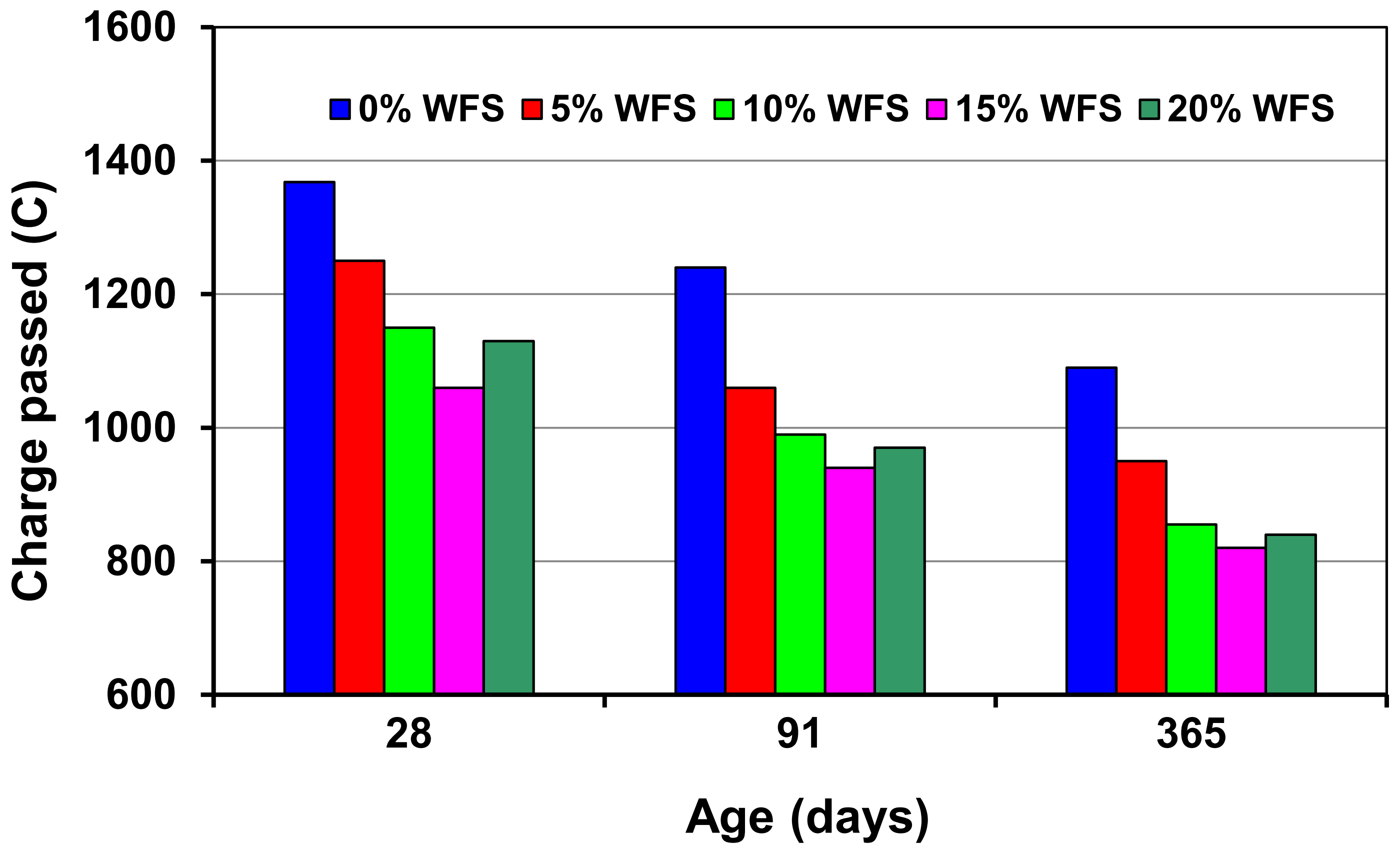
Elastic Modulus



- *Control mix proportion 1:1.23:2.53 (Cement 450 kg/m^3; w/c 0.42)*
- At 28 days, MOE of control concrete (0% WFS) - 29.9 Gpa
- At 91 days ,an increase of MOE was 2.6, 3.8, 6.1 and 5.7% from control
- At 365 days, 15% WFS showed MOE 34.1 GPa (5.6% increased from control)

Singh and Siddique (2012) Construction and Building Materials, 28, 421-426

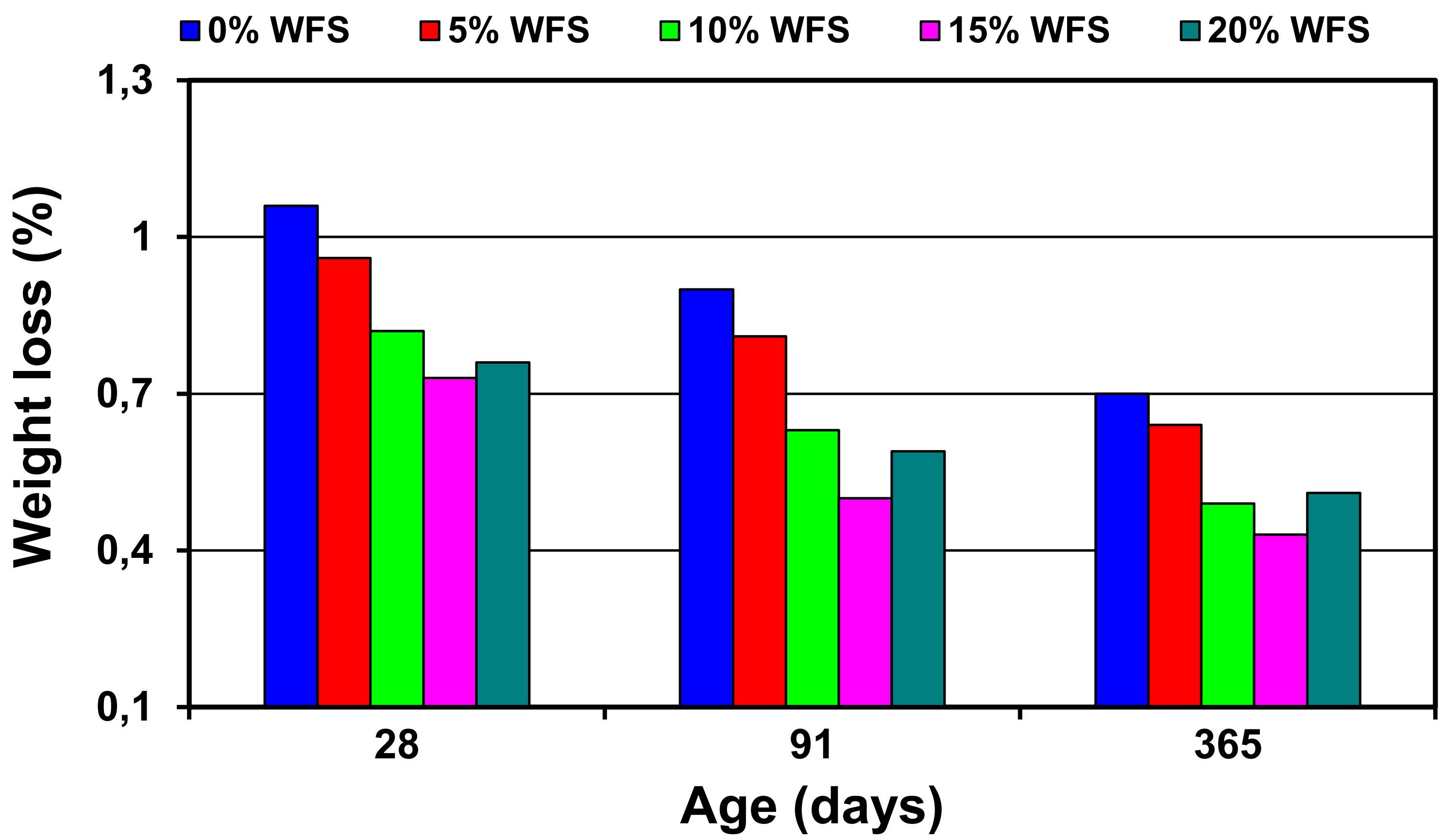
Rapid Chloride Permeability



- Chloride permeability ranges from 1368 to 820 coulombs at all ages
- At 91 & 365 days, permeability is very low in 15% WFS concrete mix
- Indicated that concrete microstructure become denser at 365 days

Singh and Siddique (2012) Construction and Building Materials, 28, 421-426

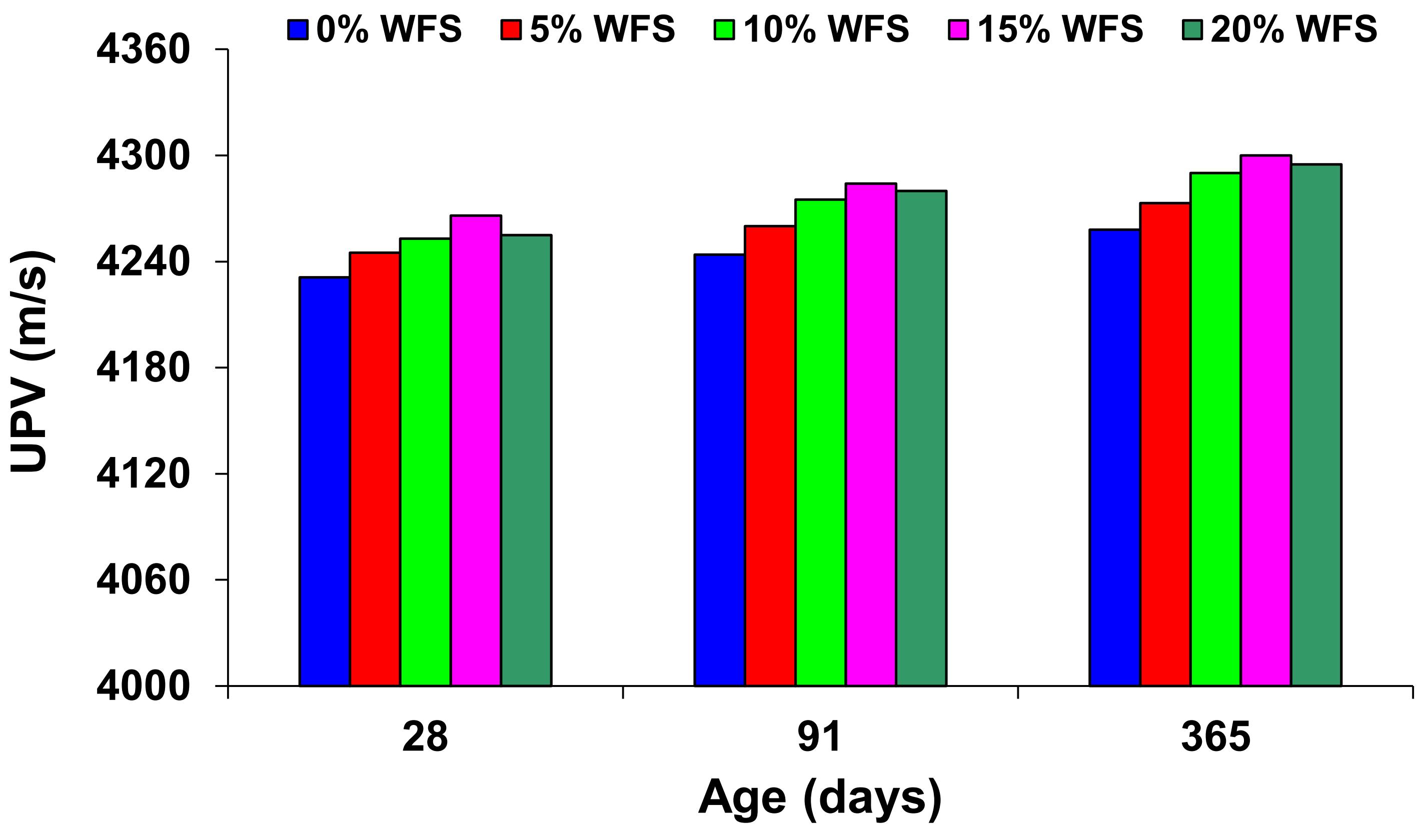
Deicing Salt Scaling Resistance



- Mass loss was observed 1.06 to 0.73% at 28 days,
- 0.9 to 0.6% at 91 days
- 0.7 to 0.42% at 365 days in 15% WFS Concrete.

Singh and Siddique (2012) Construction and Building Materials, 28, 421-426

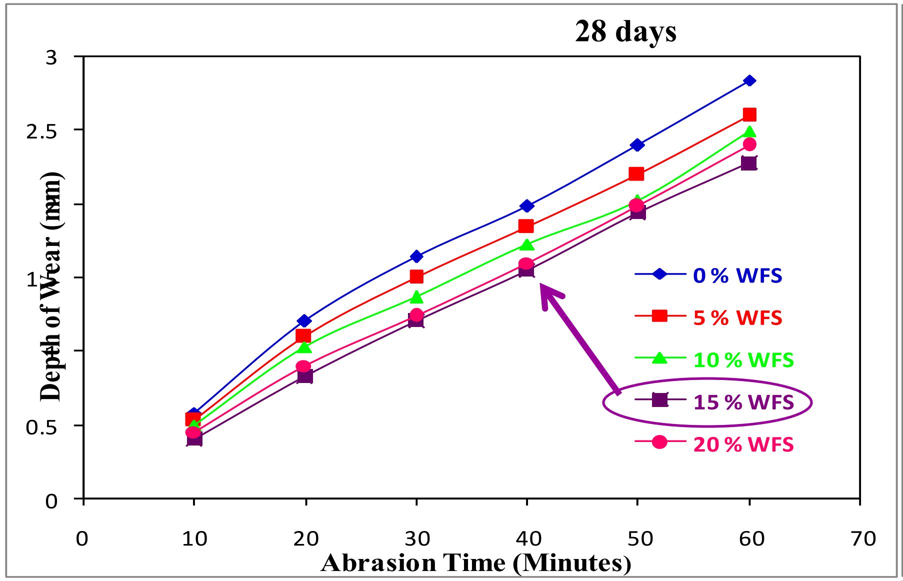
Ultrasonic Pulse Velocity

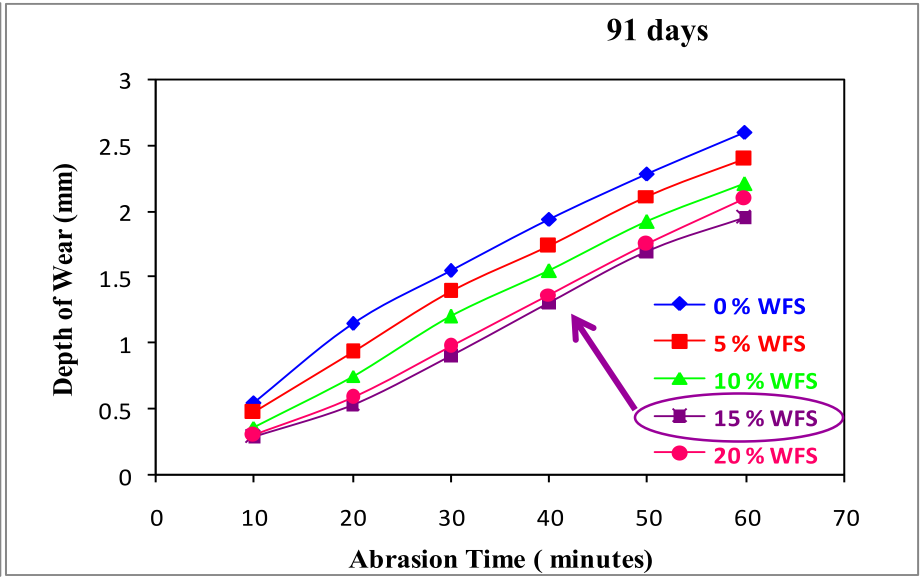


- UPV varied between 4231 m/s and 4284 m/s for all mixes at all ages
- At 28 days, maximum UPV was observed at 15% WFS
- According to BIS 13311 (part 1):1992, all mixes come under the zone of “good quality” concrete and satisfied ASTM 597-93

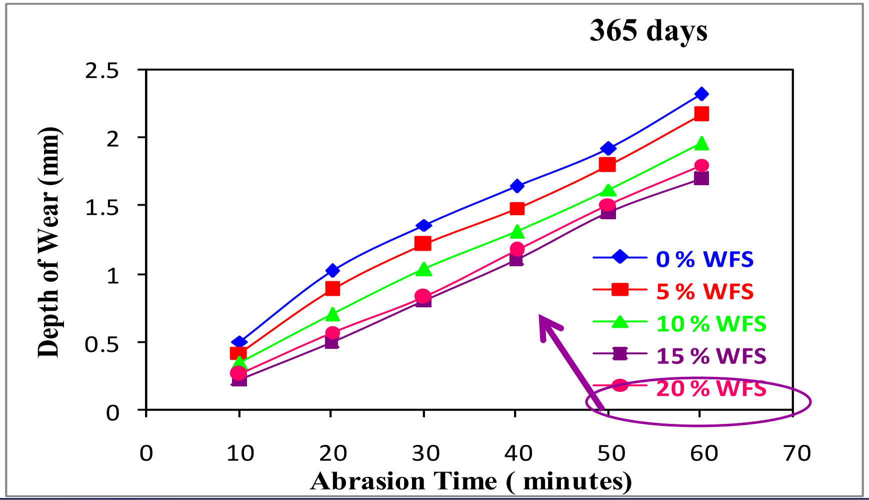
Singh and Siddique (2012) Construction and Building Materials, 28, 421-426

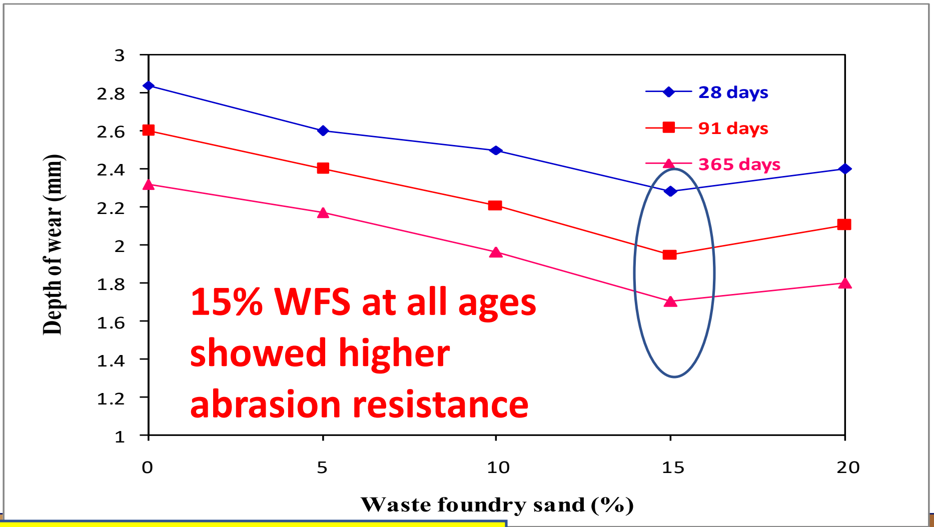
Abrasion Resistance





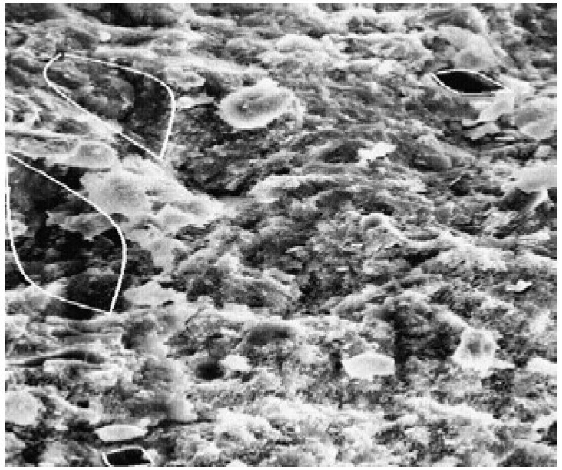
15% WFS exhibited higher resistance





Singh and Siddique (2012) Construction and Building Materials, 28, 421-426

SEM Analysis of WFS Concrete



Control

10% WFS

20% WFS

30% WFS

- All treatments showed reduced voids and C–S–H gel paste compared to control mix.
- Better spread of C–S–H gel was observed to increase from F20 to F50 mix with maximum for F30 mix.
- Findings of SEM were in accordance with the results obtained for strength

Siddique et al. (2011), Construction and Building Materials, 25, 1916-1925

Conclusions

- Replacement of fine aggregate with WFS enhanced the strength properties of concrete with the increase in WFS content at all ages and further there was continuous improvement in all these properties with the increase in curing time.

- Inclusion of WFS decreased the chloride ion penetration in concrete, which indicates that concrete has become denser and impermeable

- Different studies reported 15-30% use of WFS in concrete without compromising the strength and durability

Waste Glass

Glass

- Glass, a transparent material - melting a mixture of materials (silica, soda ash, and $CaCO_3$) at high temperature – cooling –solidification

- Two types of waste glasses – colored and colorless. Most colorless waste glasses are recycled effectively

- Colored waste glasses – low recycling rate – dumped into landfill sites

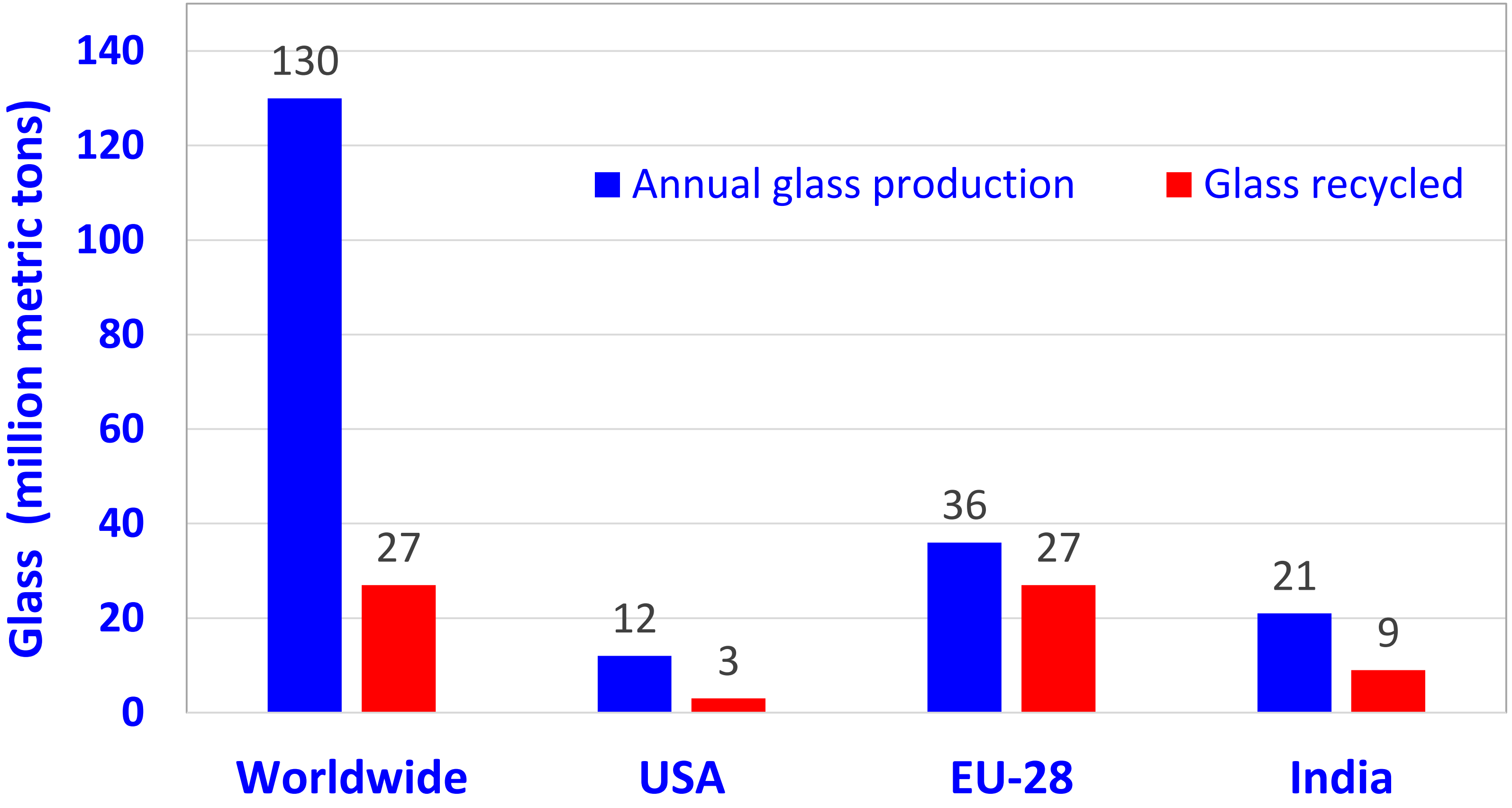
- Shortage of landfill sites – difficult in land filling

- Non – biodegradable, thus land-filling not an environment-friendly solution

Therefore, there is strong need to utilize waste glasses

Glass Type	Main Products
Soda lime glass	Bottles and jars, Tableware Flat glass
Lead glasses	Crystal tableware, Television screens, Display screens
Borosilicate glasses	Glass fiber, Wool insulation Ovenware
Technical glasses	Scientific, Frits, Optical

Glass Recycling Rates In Various Countries

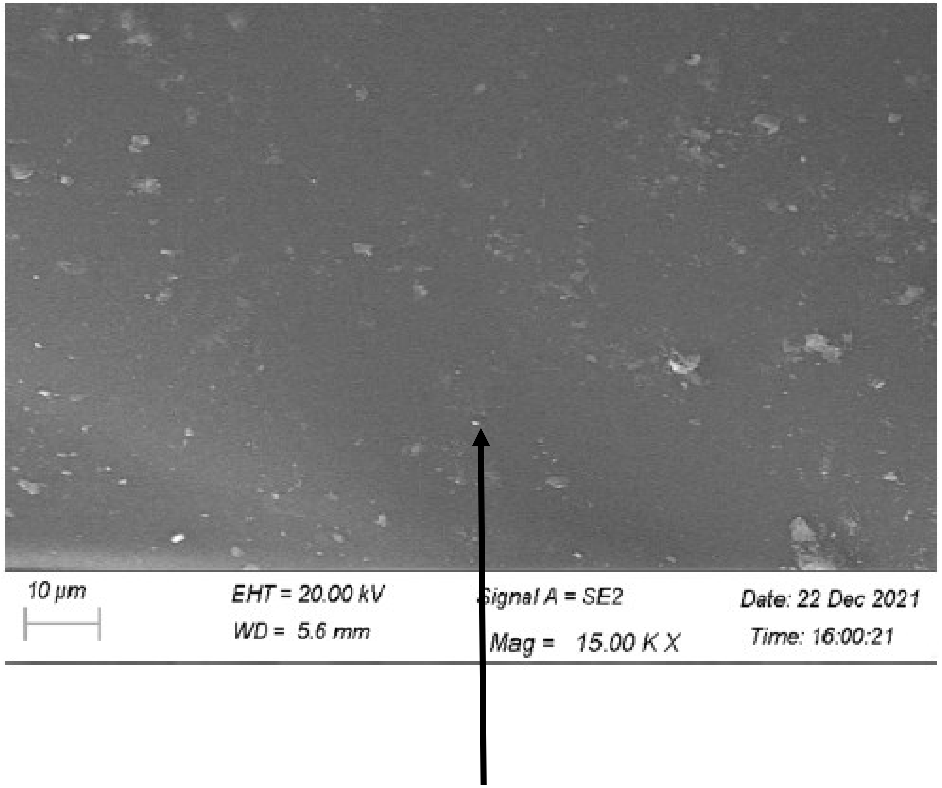


Properties

Physical Property	Value
Particle shape	Angular
Surface morphology	Even texture
Specific Gravity	2.2-3.0
Particle size (mm)	0.15-6
Water Absorption (%)	0-0.5

Constituent (%)	Value
SiO_2	70-73
Al_2O_3	1.7-2.0
Fe_2O_3	0.06-0.24
Cr_2O_3	0.1
CaO	9.1-9.8
MgO	1.1-1.7
BaO	0.14-0.18
Na_2O	13.8-14.4
K_2O	0.55-0.68
PbO	-

SEM micrograph of crushed glass particle

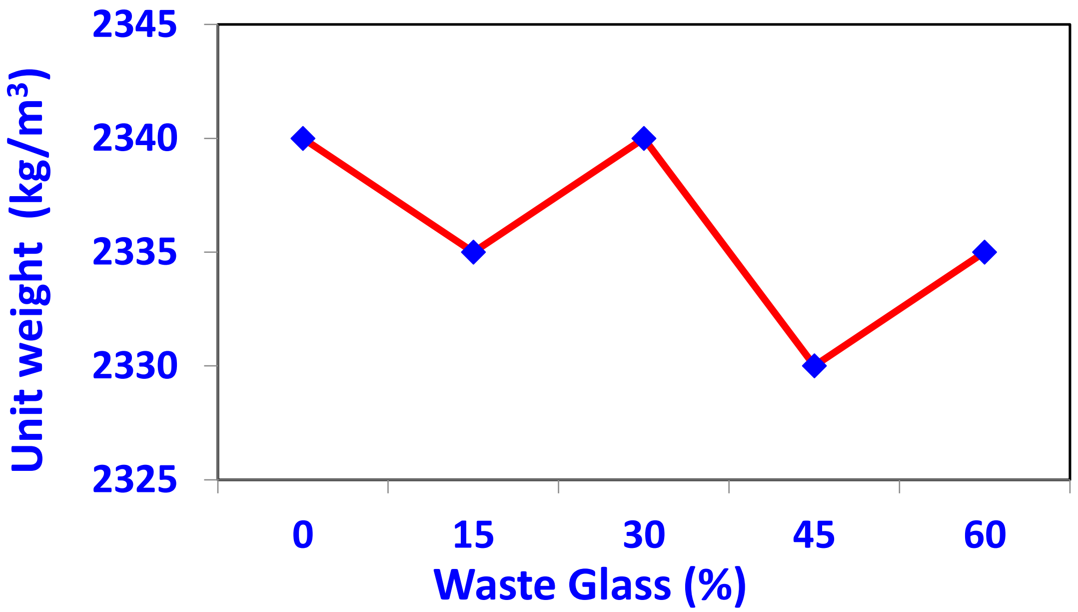


Glass particle exhibits smooth non-porous surface

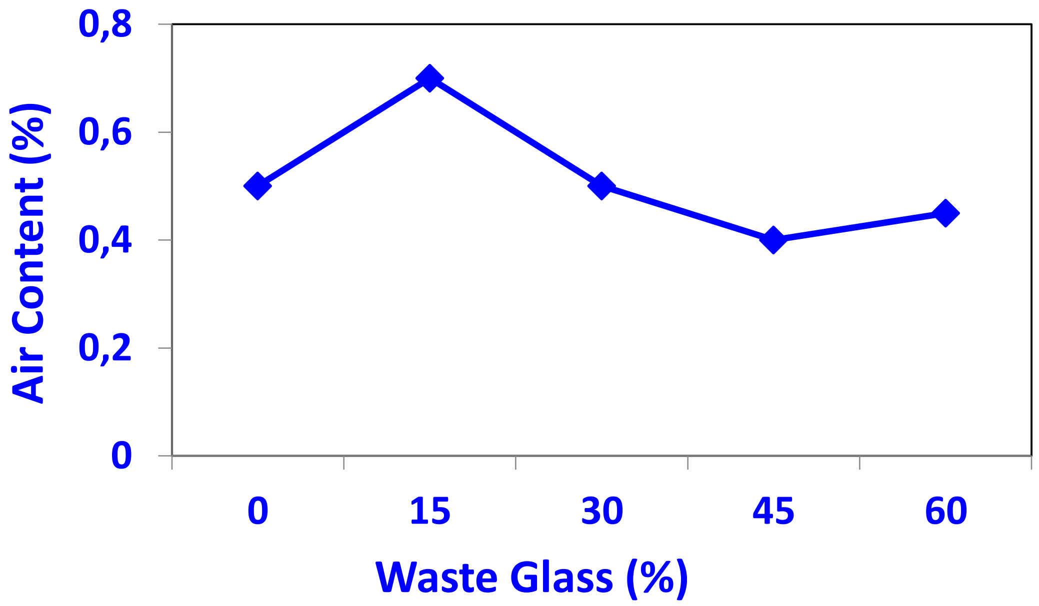
USES OF WASTE GLASS

- Asphalt Concrete Aggregate
- Granular Base or Fill
- In Cement Mortar and Concrete
- As Aggregate in Recycled Asphalt Pavement (RAP)

Unit Weight



Air Content

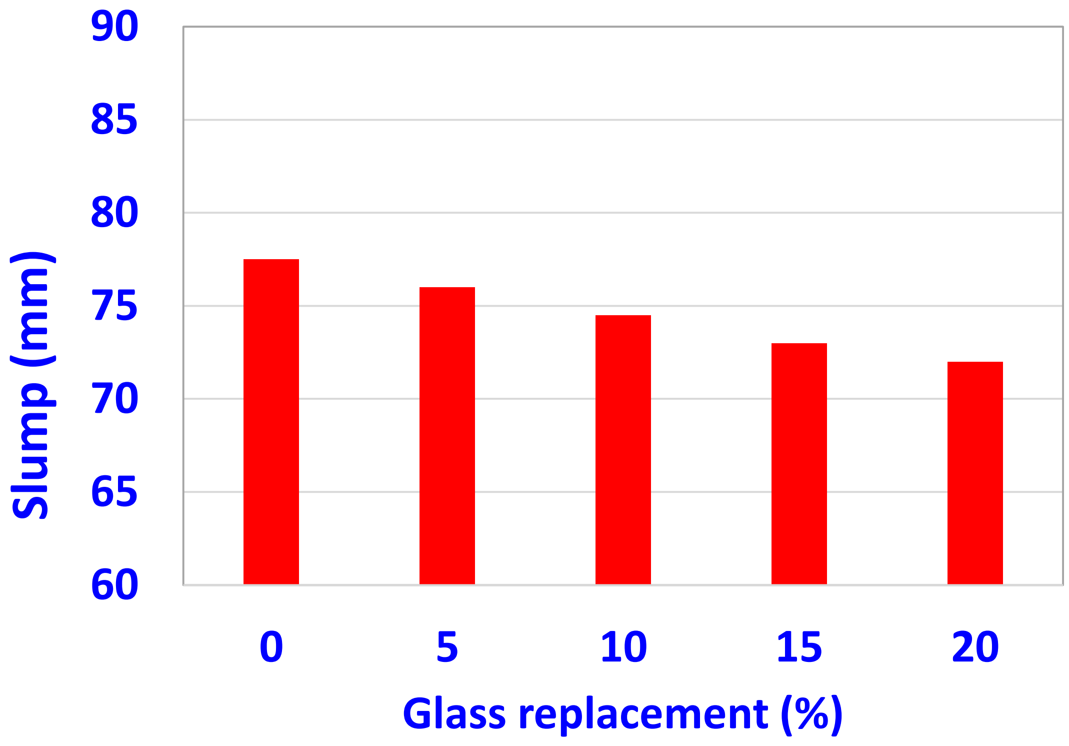


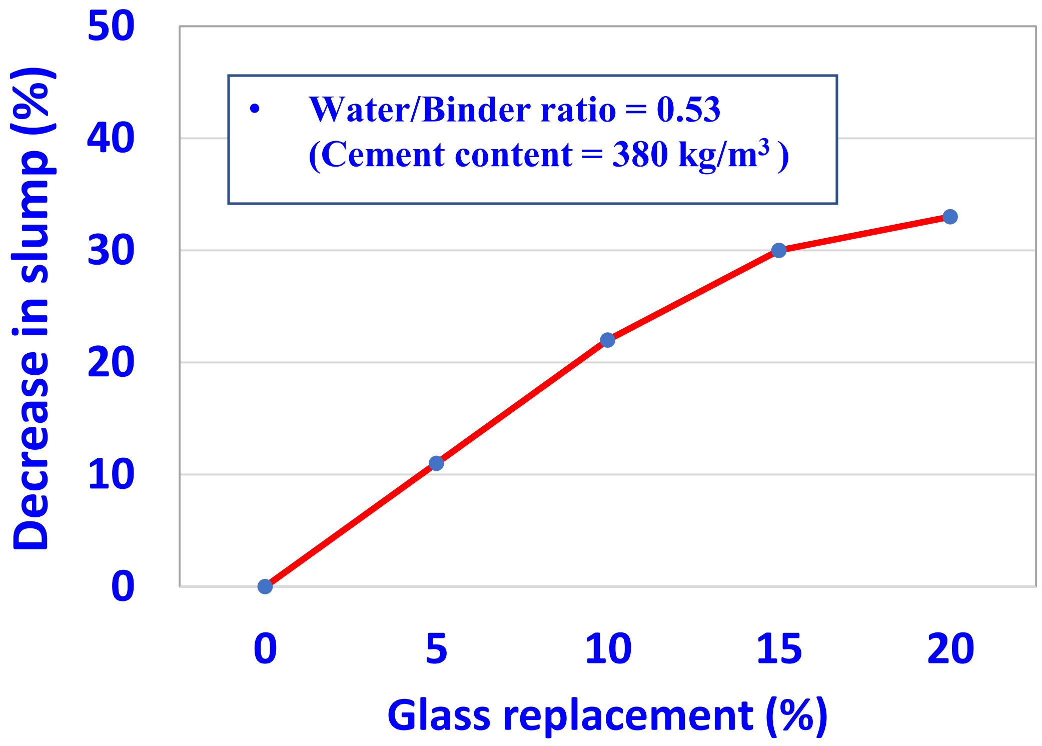
- Crushed green soda glass as coarse aggregate in concrete.
- Waste glass (WG) was used as 15, 30, 45 and 60% of the aggregate mixtures in place of calcareous crushed stone aggregates to a fineness of 4–16 mm.
- With the addition of WG, there was linear decrease of 0.3% in unit weight.

- Air content of the concretes containing waste glass up to 60% was 0.4–0.7%,
- High proportion of waste glass addition unevenly decreased the air content by as much as 27%.
- Smooth surface of waste glass helps decrease porosity between waste glass and cement paste.

Topcu and Canbaz (2004) Cement and Concrete Research 34: 267–274.

Slump





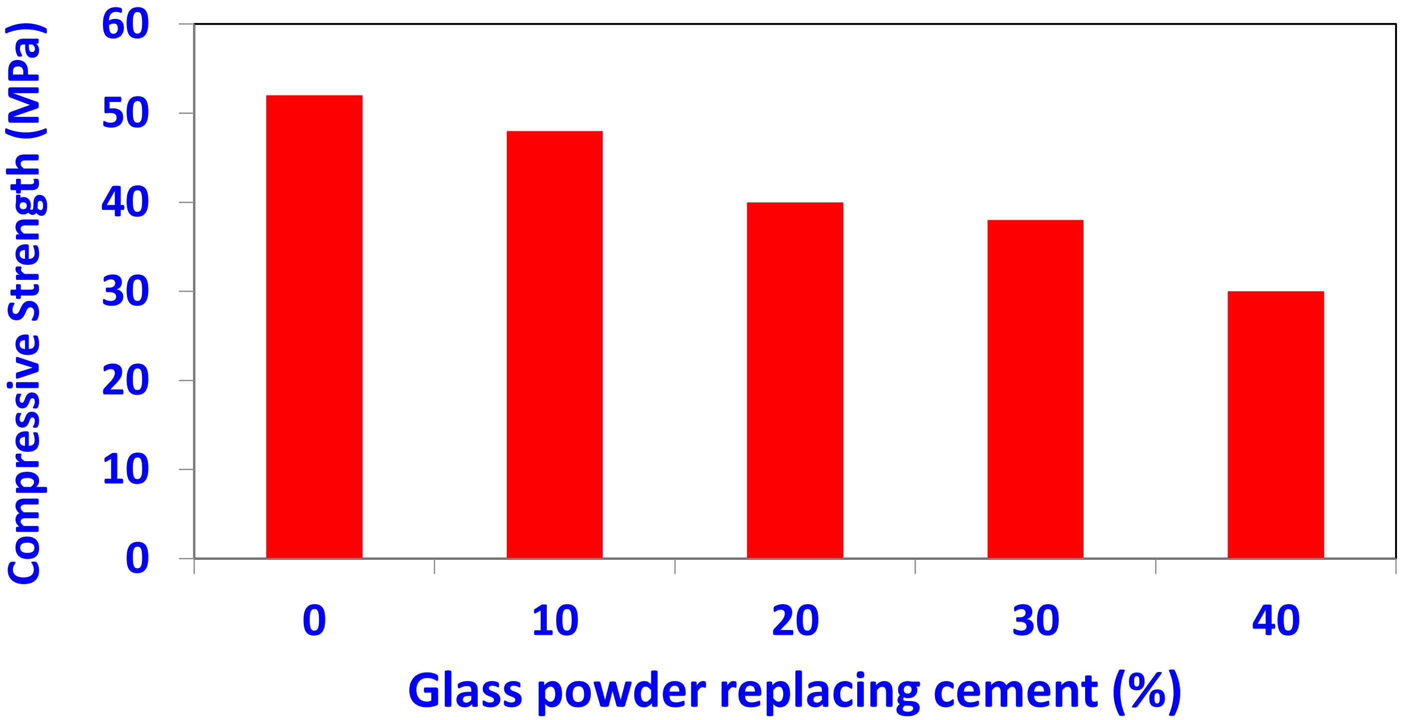
- Water/Cement ratio = 0.56 (Cement content = 446 kg/m^3)
- No admixture was used
- Slight reduction in slump is observed

- No SCM or chemical admixture used
- Workability declined as glass increased—> poor geometry of glass particles

Batayaneh et al. (2007) Waste management, 27, 1870-1876

Ismail and Hashmi (2009) Waste Management, 29, 655-659

Compressive Strength

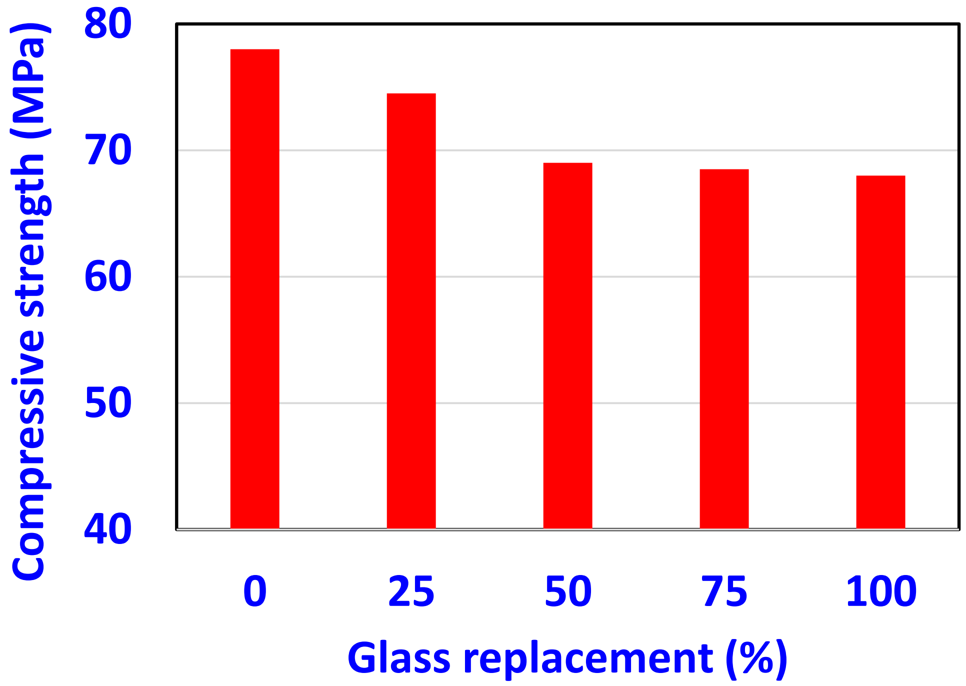


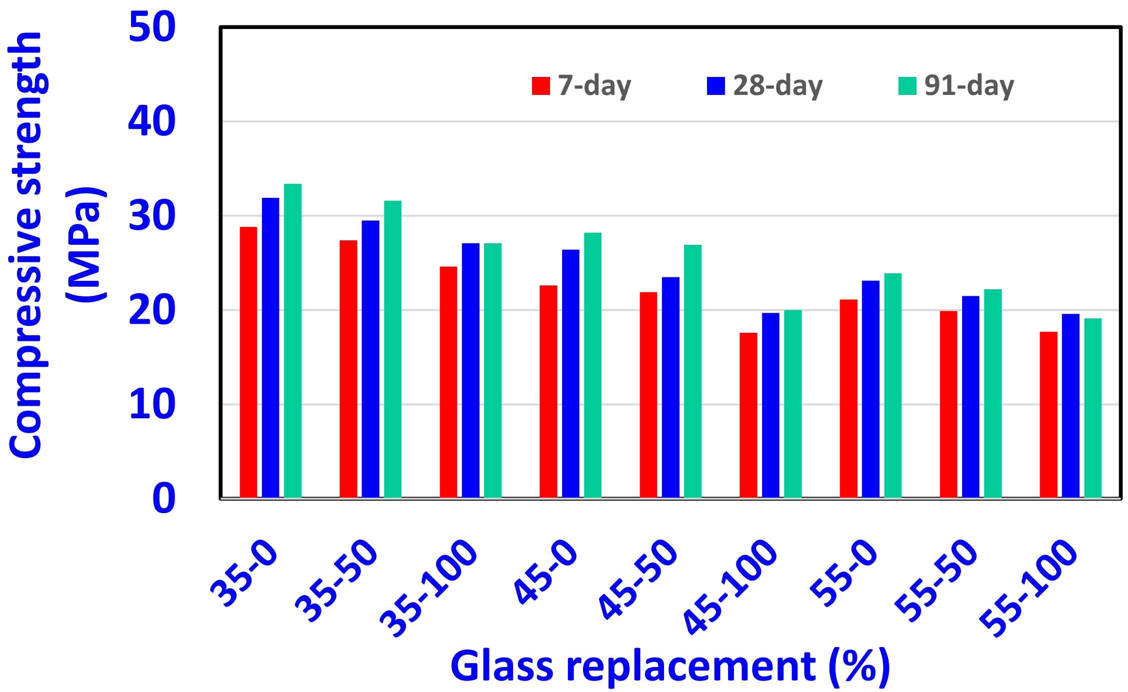
- Effect of cement and sand replacement by glass powder (GLP) on the strength of mortar cubes (aggregate/ cement ratio - 2.25 and w/c - 0.47). GLP had particle size less than 10 um and specific surface area of 800m^2/kg

- In case of cement replacement, compressive strength of the mortar decreased with the increase in GLP replacement percentage

Shayan and Xu (2004) Cement and Concrete Research 34: 81–89.

Compressive Strength





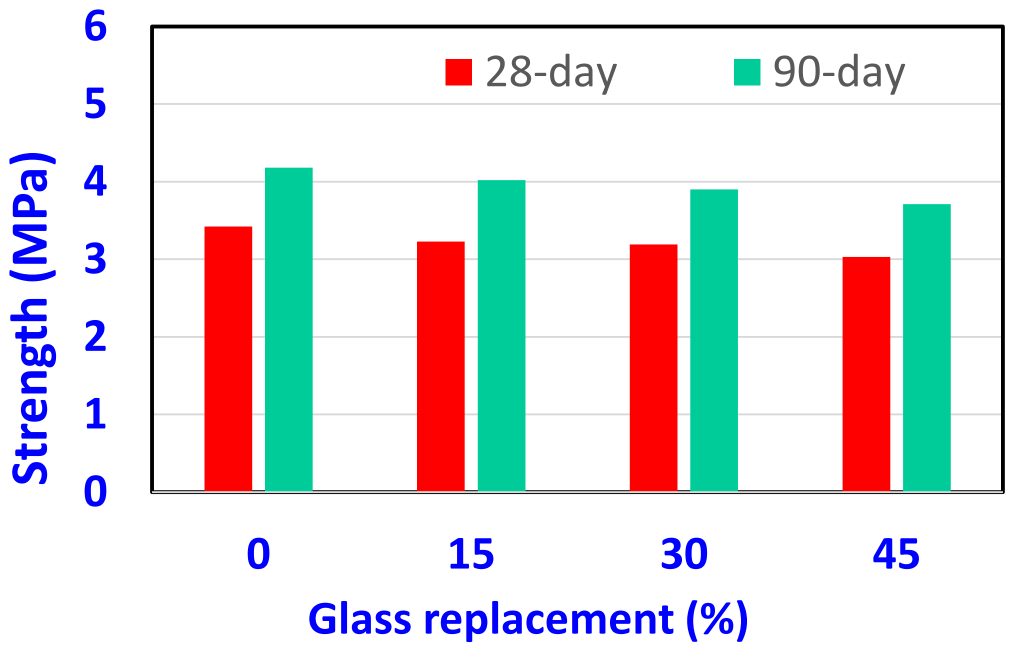
- Water/ binder ratio = 0.35 (Cement content = 467 kg/m^3)
- Fly ash content = 156 kg/m^3
- Decrease in strength —> lower adhesion between glass and cement paste

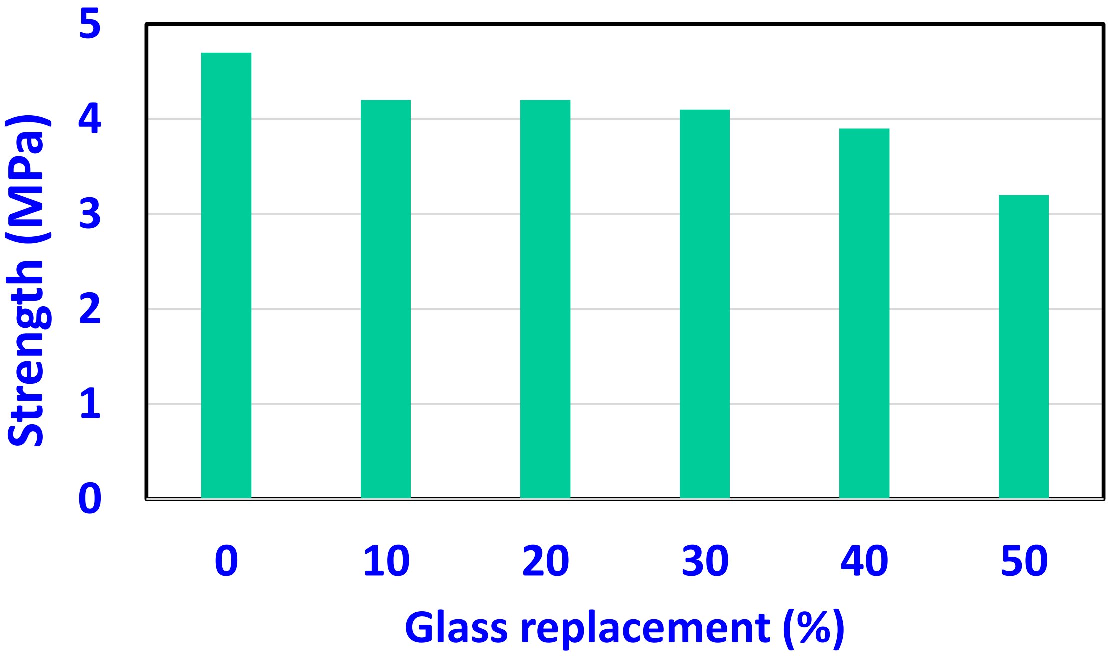
- Three Water/Binder ratios = 0.35 (Cement content = 477 kg/m^3),
  0.45 (Cement content = 378 kg/m^3)
  0.55 (Cement content = 315 kg/m^3)
- Decrease in strength as glass increased —> lower bond strength between glass and cement paste

Ling et al. (2012) Cement and concrete composites, 2012, 265-272

Kim et al. (2018) Construction and Building Materials, 184, 269-277

Split Tensile Strength





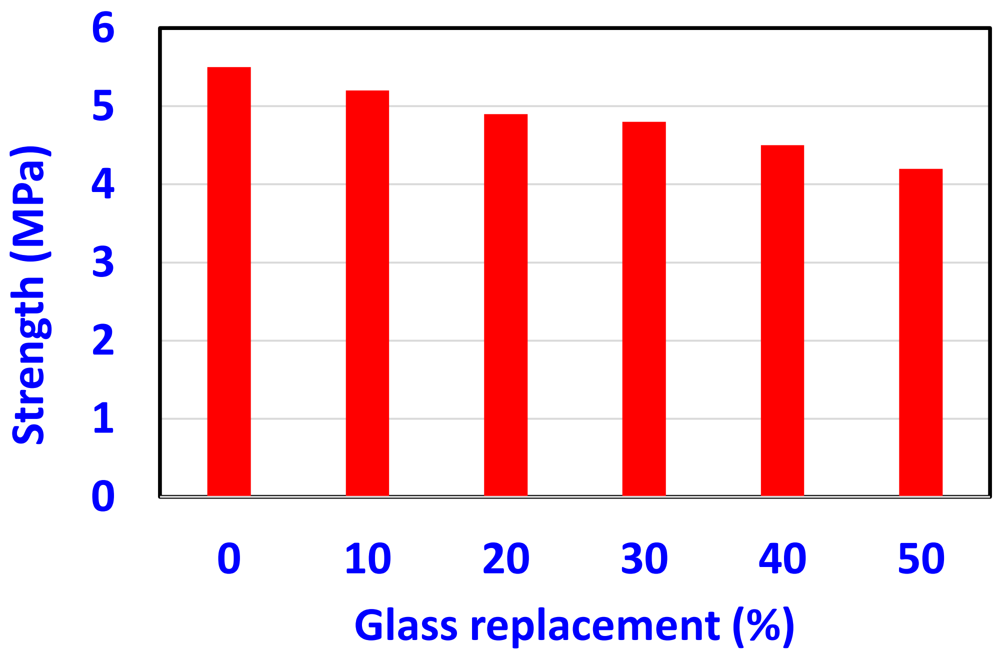
- Water/Binder ratio = 0.37 (Cement content = 375 kg/m^3)
- Pulvarised fly ash = 125 kg/m^3
- Decrease in split tensile strength —> lower adhesion between glass and cement paste

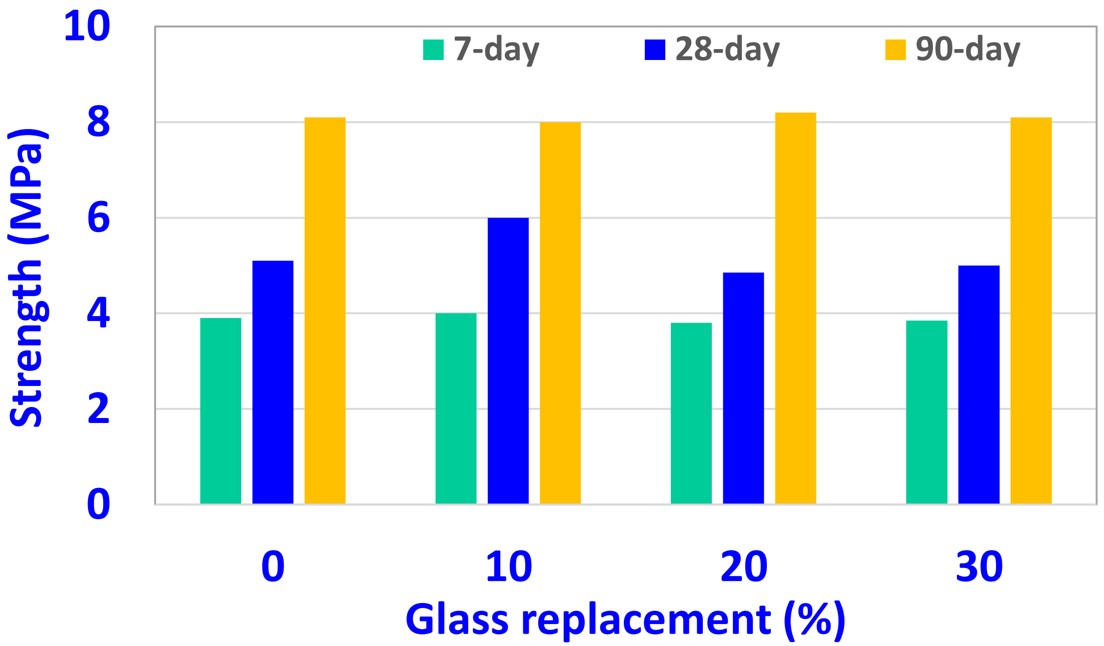
- Water/Binder ratio = 0.4 (Cement content = 350 kg/m^3)
- Silica fume = 10 % of cement content
- Smooth texture of glass particle —> weak adhesion at glass-cement paste interface —> split tensile strength decreased

Kou and Poon (2009) Cement and concrete composites, 31, 107-113

Ali and Al-Tersawy (2012) Construction and Building material, 35, 785-791

Flexural Strength





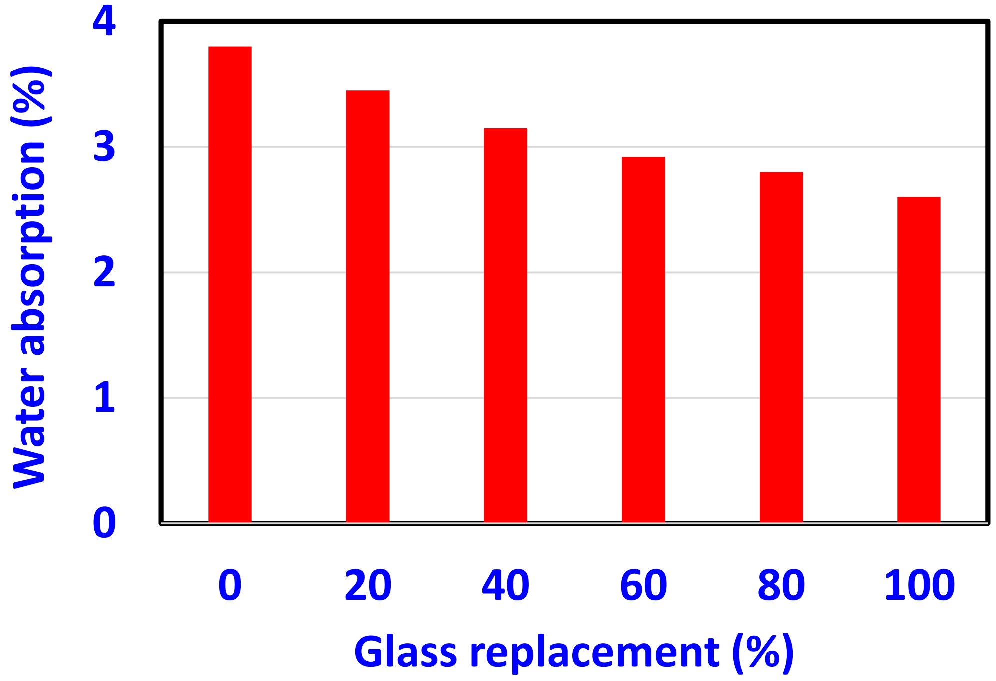
- Water/Binder ratio = 0.4 (Cement content = 350 kg/m^3)
- Silica fume = 10 % of cement content
- Smooth texture of glass particle —> weak adhesion at glass-cement paste interface —> flexural strength decreased

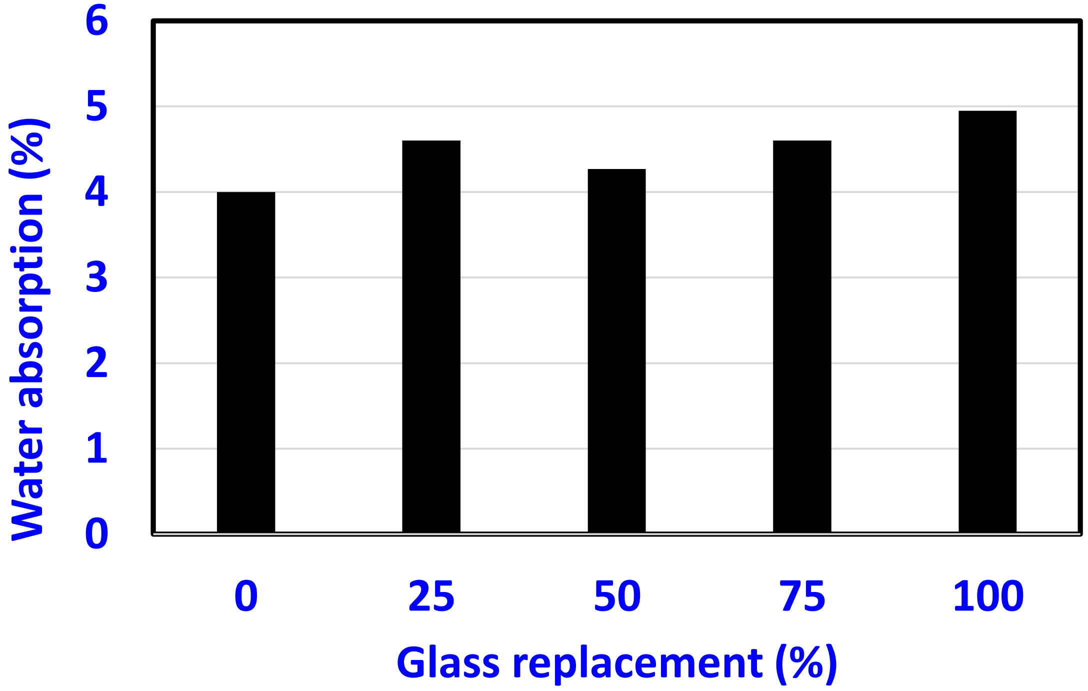
- Water/ binder ratio = 0.28 (Cement content = 463 kg/m^3)
- Fly ash content = 132 kg/m^3
- No significant change in flexural strength is observed

Ali and Al-Tersawy (2012) Construction and Building material, 35, 785-791

Wang and Huang (2010) Construction and Building Materials, 24, 1008-1013

Water Absorption by Immersion





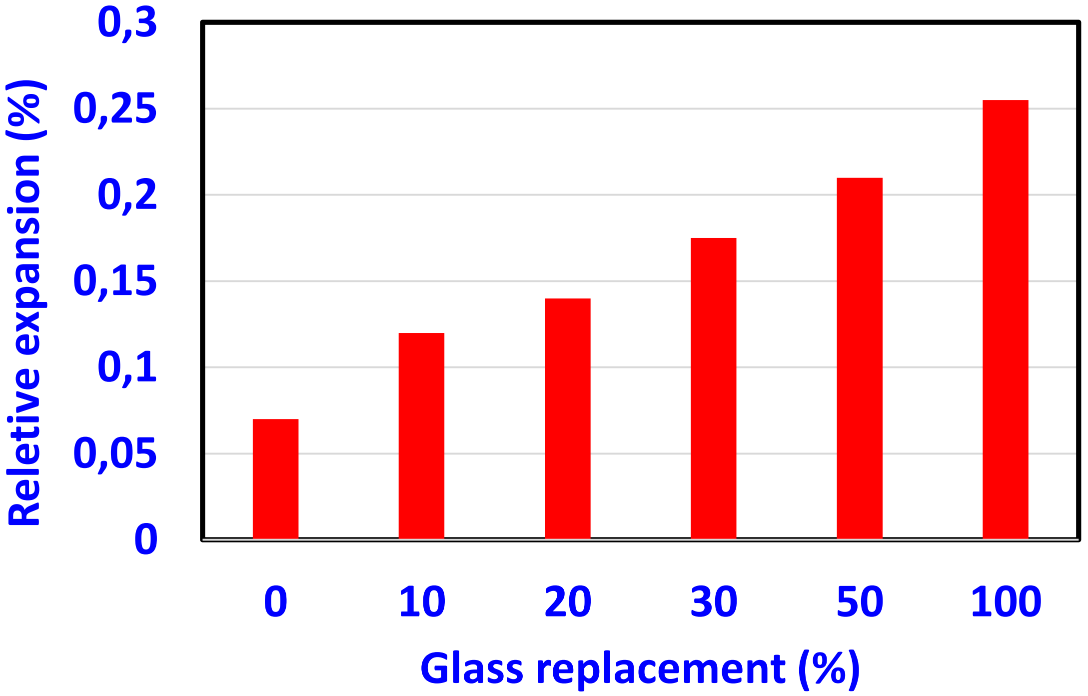
- Water/cement ratio = 0.45 (Cement content = 336 kg/m^3)
- SCM used = fly ash (84 kg/m^3)
- Water absorption decreased as glass content decreased —> Lower water absorption of glass as compared to sand

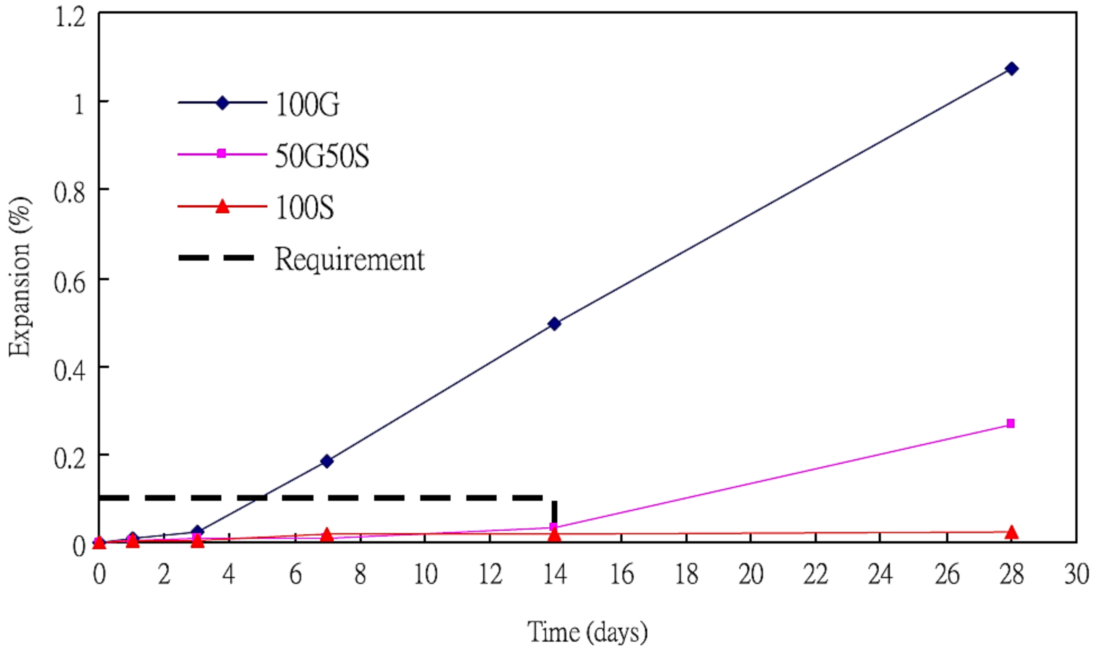
- Water/cement ratio = 0.27 -0.24 (Cement content = 480 kg/m^3)
- W/C ratio decreased as glass content increased with 0.24 at 100 % replacement
- Water absorption increased as glass content decreased

Song et al. (2019) Construction and Building Materials, 202, 332-340

Lee et al. (2013) Construction and Building Materials, 38, 638-643

Alkali-silica reaction





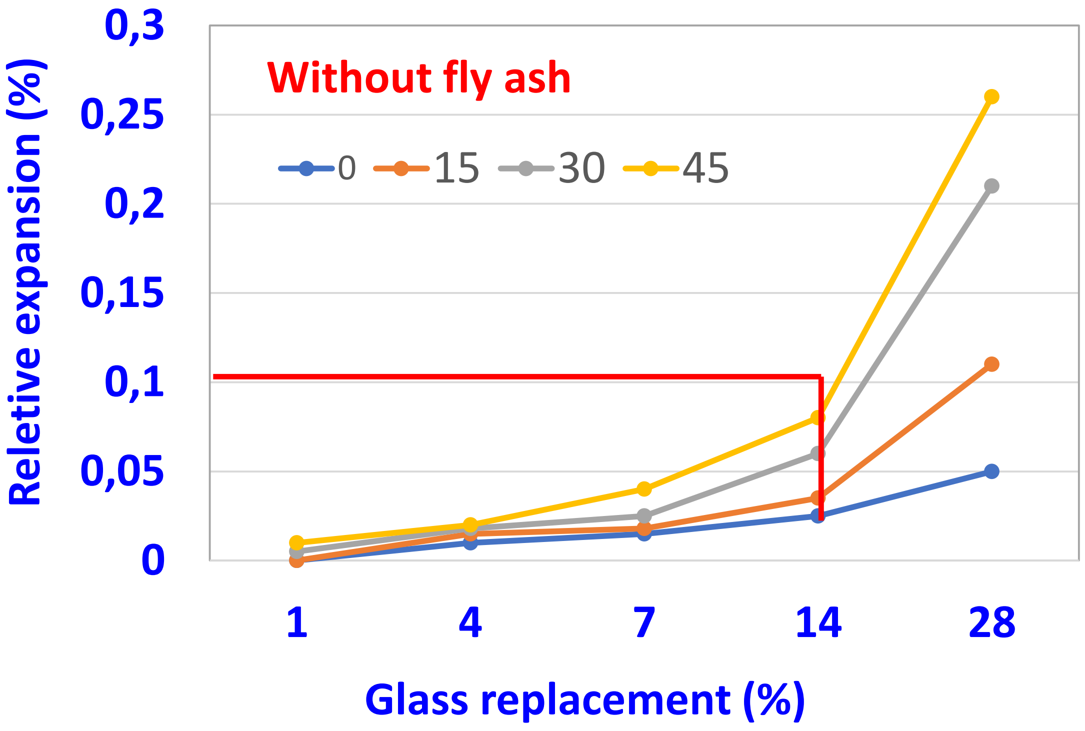
- Mortar bars with waste glass display a relatively higher expansion
- Glass incorporated mortar bars showed an expansion of 1.8 –3.9 times that of plain mortar bars
- Expansion was due to the unlimited supply of alkali in the 1 N NaOH solution which reacts with amorphous silica of glass to produce deleterious expansive gel

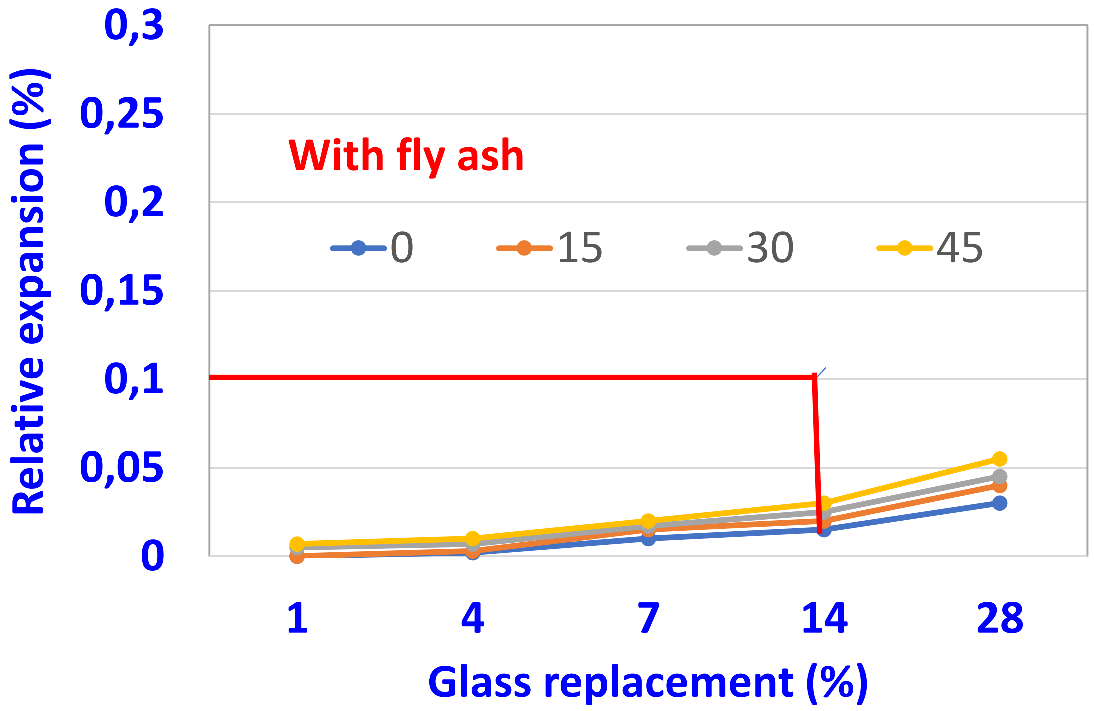
- Glass type : Mixed glass (size: 0.15 mm – 6 mm)
- Mortar bars with 100 % glass waste displayed a relatively higher expansion
- Mortar bars prepared with 50% glass and 50% sand were able to meet the requirements at 14 days

Park et al. (2004) Cement and Concrete Research, 34, 2181-2189

Lam et al. (2007) Cement and Concrete Composites, 29, 616-625

Alkali-Silica Reaction

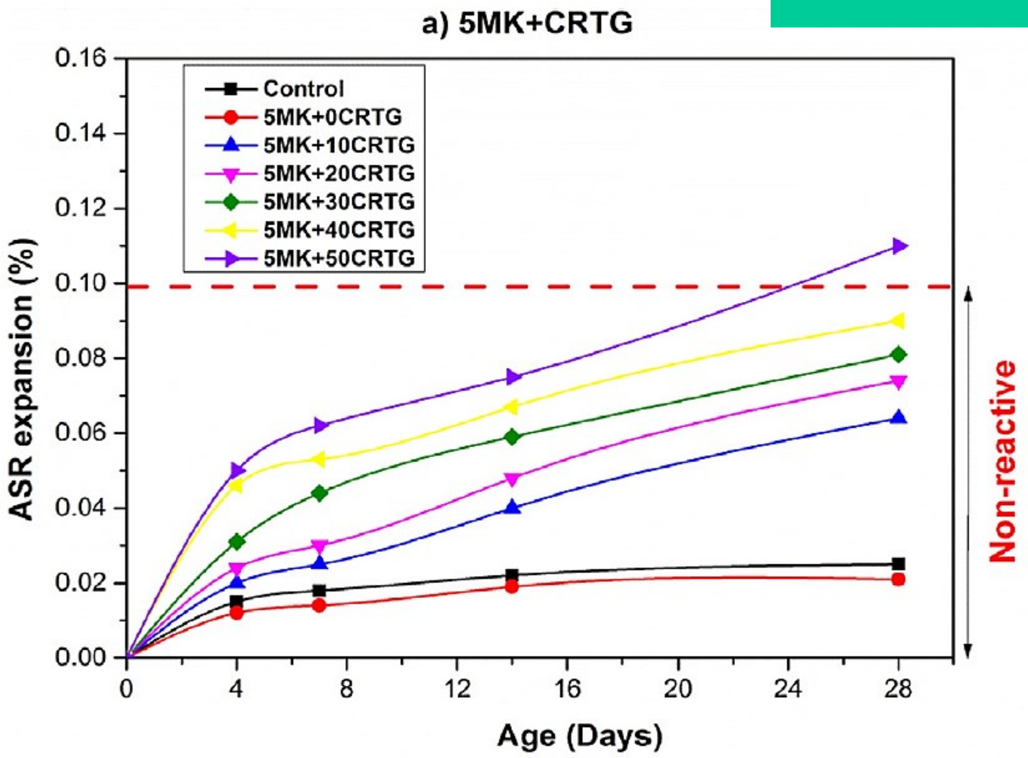


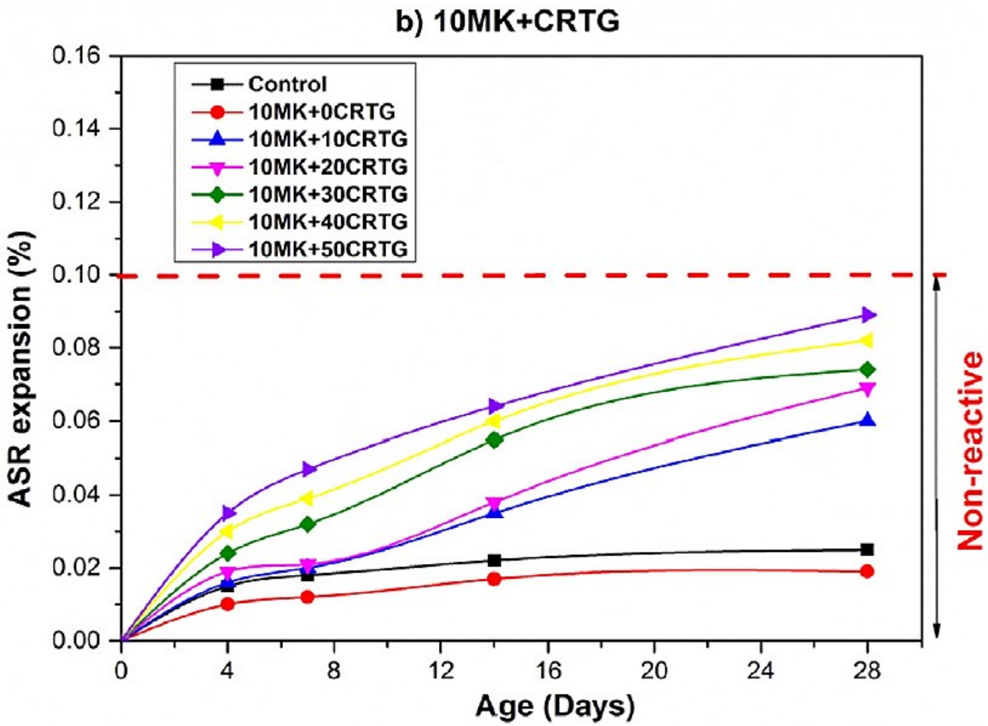


- Glass type: Waste beverage bottle glass
- Fly ash was used to substitute 15 % of total sand content in second series of mortar bars
- Fly ash can significantly supress ASR expansion
- Pozzolanic reaction consume OH^- ions and reduce the pH, thus slowing down the ASR.

Kou and Poon (2009) Cement and Concrete Composites, 31, 107-113

Alkali-Silica Reaction

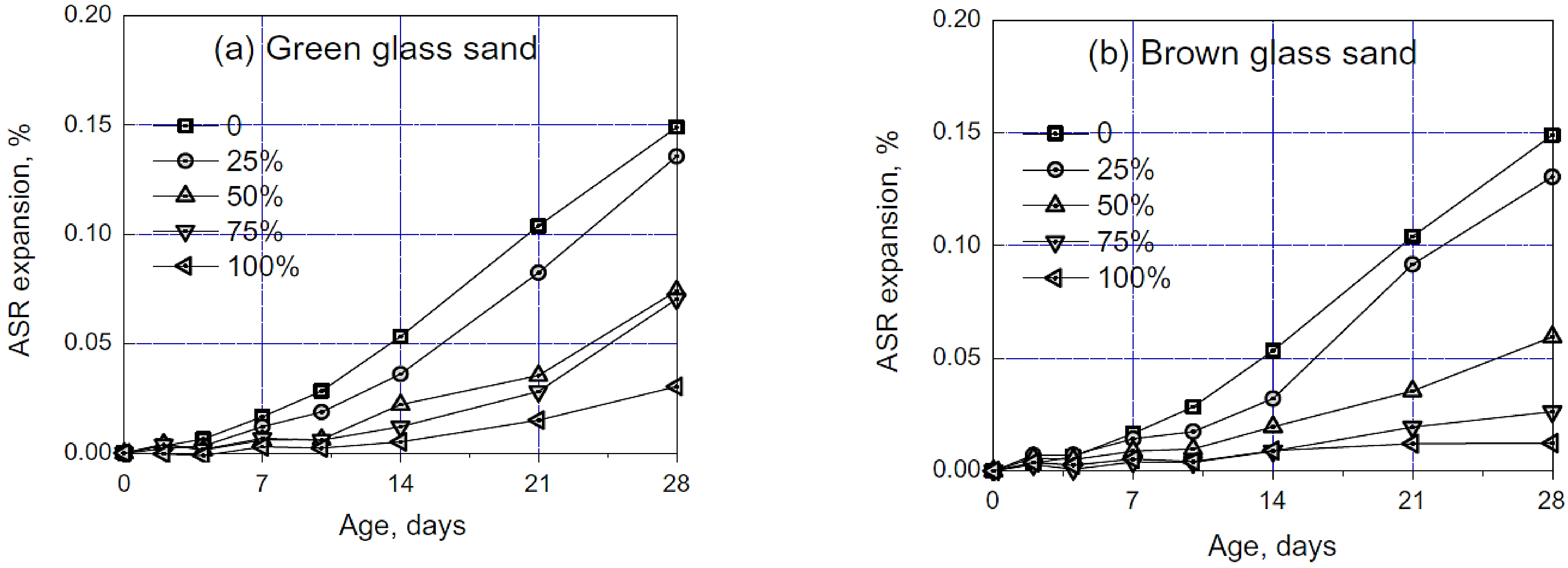




- Glass type: Cathode ray tube glass (size: 0.15 mm – 4.75 mm); Water/Binder ratio = 0.4 (Total binder content = 470 kg/m^3)
- Metakaolin used as 5 % and 10 % cement substitute
- ASR expansion increased with glass content —> higher SiO_2/CaO ratio
- **Higher percentage of MK is effective in reducing ASR expansion —> pozzolanic reaction can reduce SiO_2/CaO ratio**

Ouldkhaoua et al. (2020) Construction and Building Materials, 235, 117802

Alkali-Silica Reaction



- Glass type : Green and brown (size: 0.15 mm – 4.75 mm)
- No potentially deleterious expansion observed —> equivalent alkali content much lower than that of container glass
- Green and brown glass is least reactive in ASR due to its high content of Cr_2O_3

Du and Tan (2013) Cement and Concrete Composites, 35, 118

Thank you very much for your patience