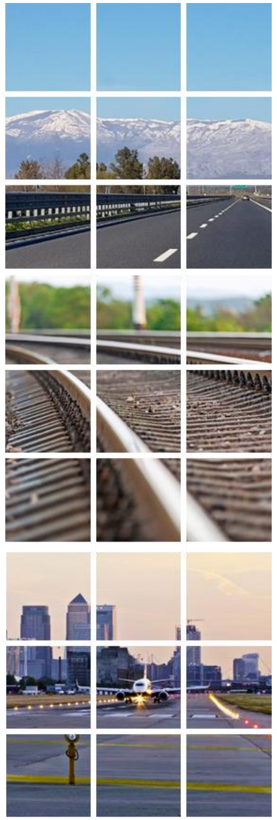
Transportation Infrastructures towards Green Transition

Società Italiana Infrastrutture Viarie



Impiego di scorie da forno elettrico come aggregati artificiali di pavimentazioni stradali

4 SEPTEMBER .23

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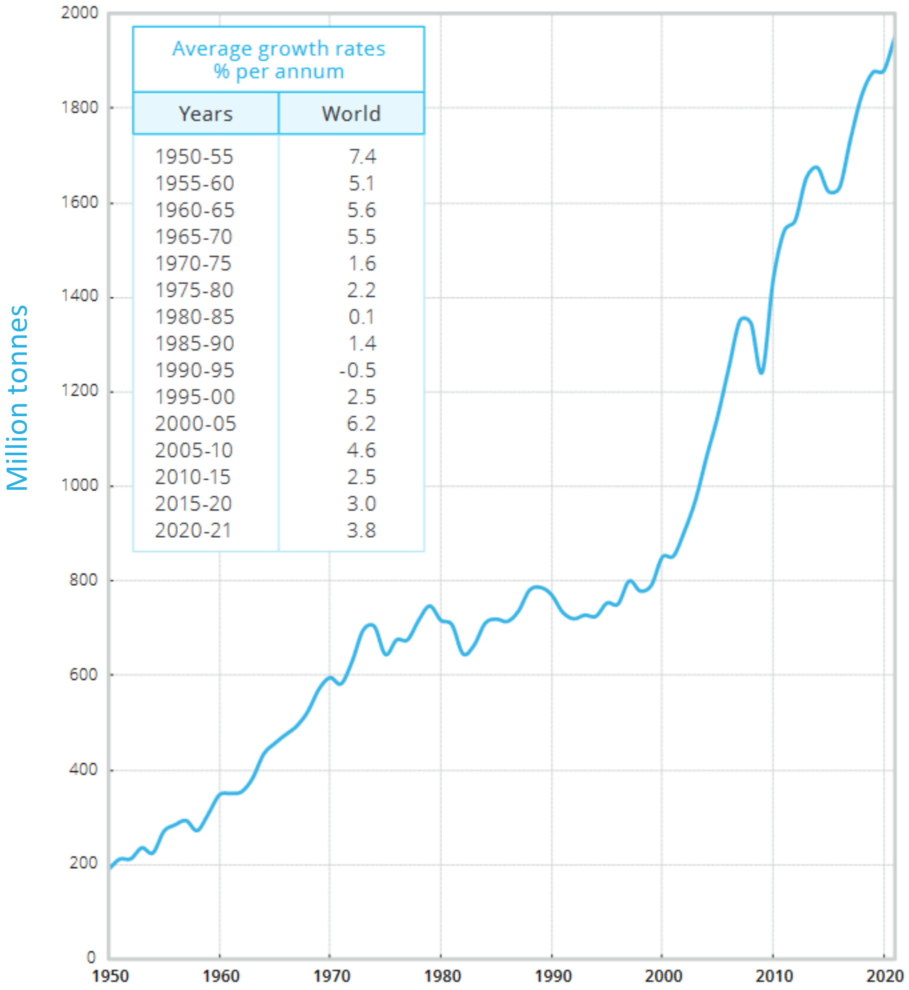
Università di Parma

UNIVERSITÀ DI PARMA

Futuro (Presente) del mondo delle costruzioni stradali

Presupposti dell’utilizzo della scoria da forno elettrico

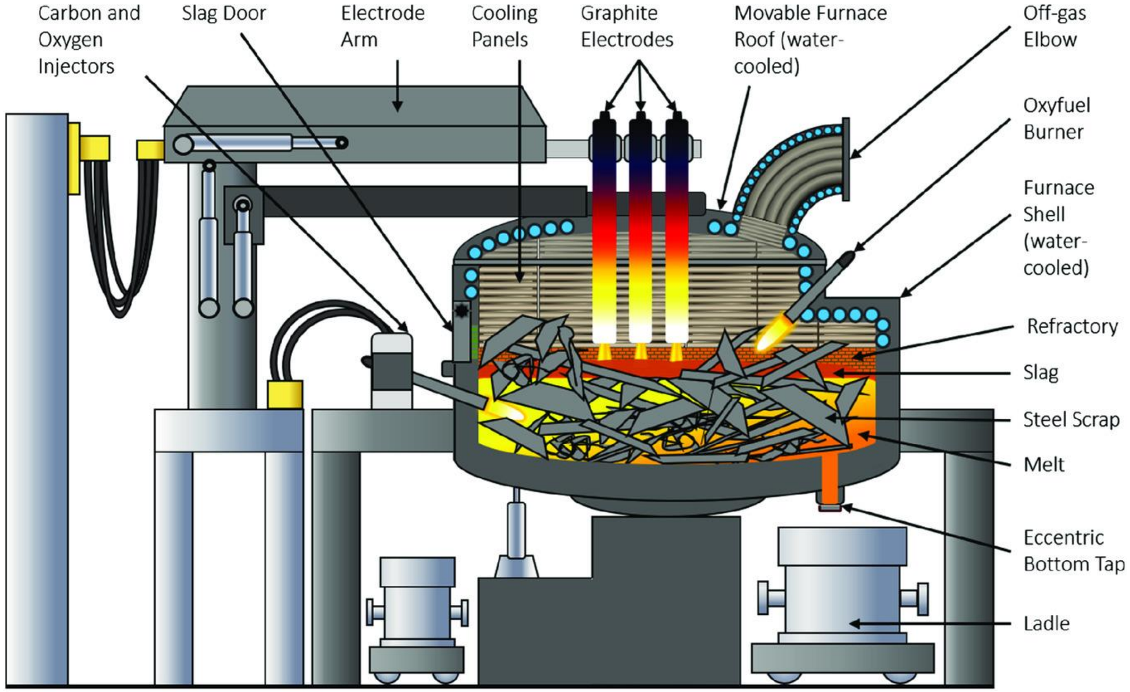
Produzione mondiale acciaio



	Million tonnes	Oxygen %	Electric %
Austria	7.9	91.3	8.7
Belgium	6.9	69.7	30.3
Bulgaria	0.5	-	100.0
Croatia	0.2	-	100.0
Czechia	4.8	96.1	3.9
Finland	4.3	60.3	39.7
France	13.9	66.8	33.2
Germany	40.1	69.8	30.2
Greece	1.5	-	100.0
Hungary	1.1	68.6	31.4
Italy (e)	24.4	16.0	84.0
Luxembourg	2.1	-	100.0
Netherlands	6.6	100.0	-
Poland	8.5	48.1	51.9
Portugal	2.0	-	100.0
Romania (e)	3.4	68.2	31.8
Slovakia (e)	4.9	80.2	19.8
Slovenia	0.7	-	100.0
Spain	14.2	31.7	68.3
Sweden	4.7	64.5	35.5
European Union (27)	152.6	56.1	43.9
Turkey	40.4	28.4	71.6
United Kingdom	7.2	81.7	18.3
Others (e)	4.7	47.1	52.9
Other Europe	52.3	37.4	62.6
Russia	75.6	59.0	39.0
Ukraine	21.4	76.0	5.8
Other CIS (e)	8.4	51.3	48.7
Russia & Other CIS + Ukraine	105.4	61.8	33.0

Canada (e)	13.0	54.7	45.3
Mexico	18.5	15.9	84.1
United States	85.8	30.8	69.2
USMCA	117.2	31.1	68.9
Argentina	4.9	54.8	45.2
Brazil	36.2	75.2	23.6
Chile	1.3	63.2	36.8
Venezuela	0.0	-	100.0
Other Central & South America (e)	3.9	6.6	93.4
Central & South America	46.3	66.8	32.2
Egypt	10.3	-	100.0
South Africa (e)	5.0	57.7	42.3
Other Africa (e)	5.1	8.6	91.3
Africa	20.4	16.1	83.9
Iran (e)	28.5	9.7	90.3
Saudi Arabia	8.7	-	100.0
Other Middle East (e)	8.7	-	100.0
Middle East	45.8	6.0	94.0
China (e)	1 032.8	89.4	10.6
India	118.2	44.8	55.2
Japan	96.3	74.7	25.3
South Korea	70.4	68.2	31.8
Taiwan, China	23.2	60.5	39.5
Other Asia (e)	62.4	35.6	64.4
Asia	1 403.4	80.7	19.3
Australia	5.8	73.6	26.4
New Zealand	0.6	100.0	-
Total of above countries	1 949.9	70.8	28.9

Produzione acciaio con forni ad arco elettrico (Electric Arc Furnace)



1 ton acciaio = 150 kg scoria (ITA ≈ 3 ton/anno)

Processazione e gestione della scoria EAF

- Scorifica alla fine del processo fusorio e di metallurgia primaria
- Scarico e raffreddamento
- Stoccaggio e stabilizzazione
- Deferrizzazione, Frantumazione e Vagliatura

SCORIA SOTTOPRODOTTO (Marcatura CE)
SCORIA RIFIUTO (Attribuzione codice CER 100202 "scorie non trattate")
SCORIA END OF WASTE: trattamento di scoria rifiuto

Infrastrutture stradali

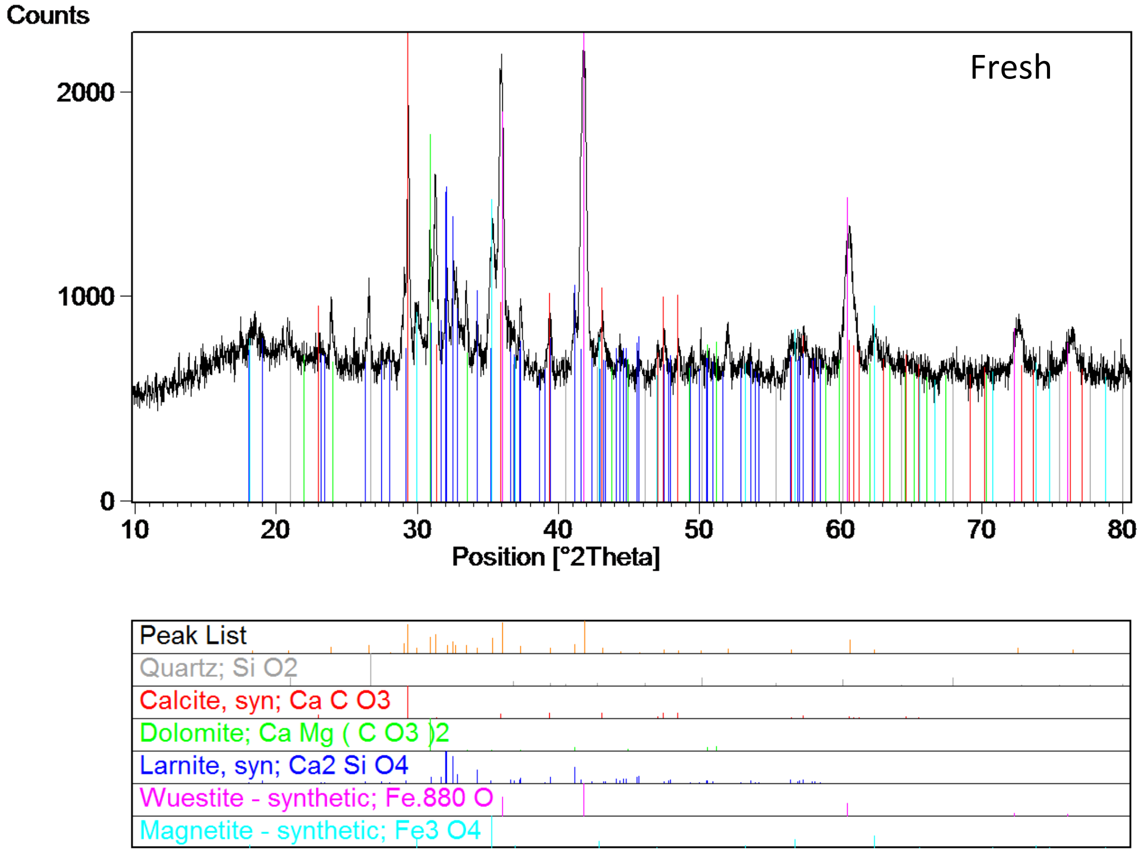
EN 12620 “Aggregati per calcestruzzo”
EN 13139 “Aggregati per malta”

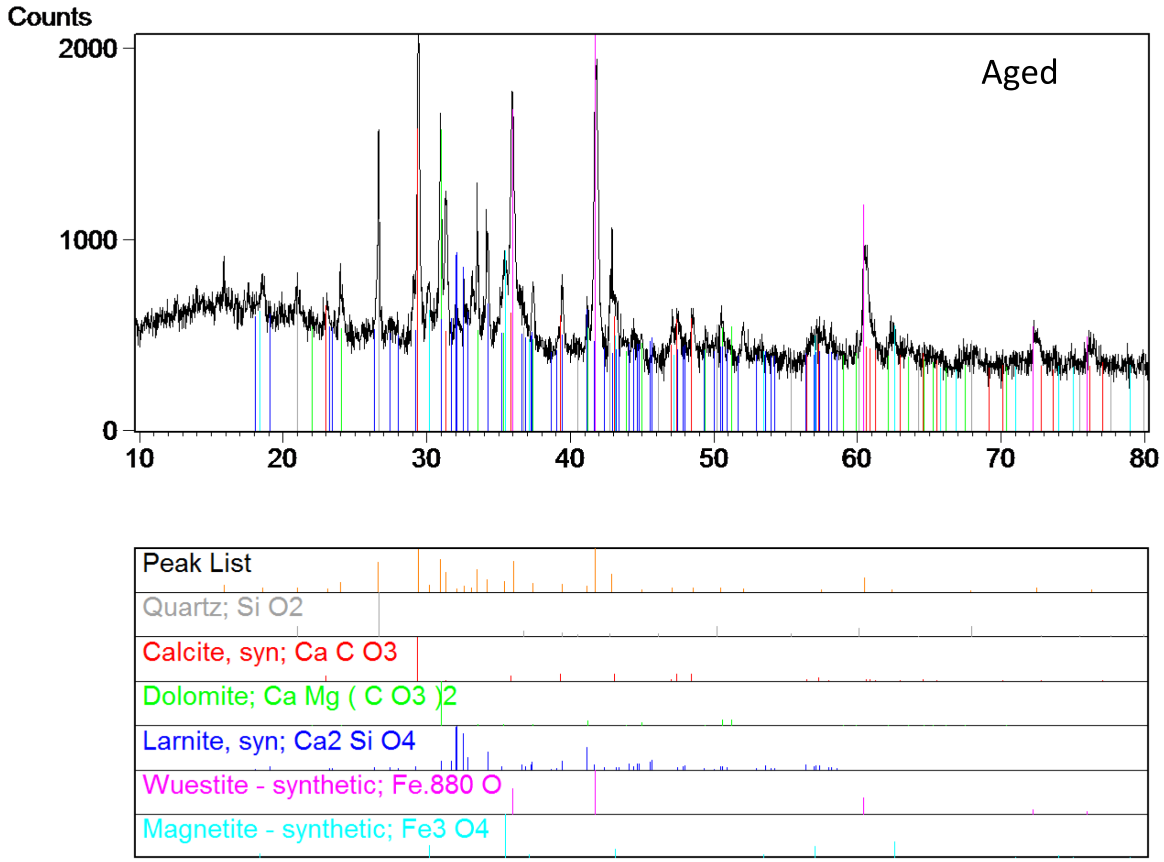
EN 13450 “Aggregati per massicciate per ferrovie”

EN 13242 “Aggregati per materiali non legati e legati con leganti idraulici per l’impiego in opere di ingegneria civile e nella costruzione delle strade”

EN 13043 “Aggregati per miscele bituminose e trattamenti superficiali per strade, aeroporti e altre aree soggette a traffico”

Cristallografia a raggi X (XRD)





Fluorescenza a raggi X (XRF)

Parameter	Value (%)	Literature values (%)
Calcium oxide (CaO)	21.79	6-48
Silicon dioxide (SiO_2)	8.77	9-32
Aluminium oxide (Al_2O_3)	7.37	3-14
Magnesium oxide (MgO)	2.15	3-15
Iron oxide (FeO)	42.99	21-48
Manganese(II) oxide (MnO)	3.80	1-16
Titanium dioxide (TiO_2)	0.25	0-1
Phosphorus pentoxide (P_2O_5)	0.33	0-2
Chromium(III) oxide (Cr_2O_5)	1.19	0-2
Sulfur (S) (%)	0.21	-
Chromium (Cr) (%)	0.84	-

$CaO + H_2O = Ca(OH)_2$ portlandite → (settimane)

$MgO + H_2O = Ca(OH)_2$ periclase → (mesi/anni)

Lisciviazione di rifiuti granulari e di fanghi (EN 12457-2)

Parameter	Value	Ministerial Decree 06/186 Limit value
Nitrates (NO_3) ($mg\ l^{-1}$)	< 1	50
Fluorides (F) ($mg\ l^{-1}$)	< 0.1	1.5
Sulphates (SO_4) ($mg\ l^{-1}$)	2.9	250
Chlorides (Cl) ($mg\ l^{-1}$)	1	100
Cyanide (CN) ($\mu g\ l^{-1}$)	< 10	50
Barium (Ba) ($mg\ l^{-1}$)	0.33	1
Copper (Cu) ($mg\ l^{-1}$)	< 0.01	0.05
Zinc (Zn) ($mg\ l^{-1}$)	< 0.01	3
Beryllium (Be) ($\mu g\ l^{-1}$)	< 5	10
Cobalt (Co) ($\mu g\ l^{-1}$)	< 10	250
Nickel (Ni) ($\mu g\ l^{-1}$)	< 5	10
Vanadium (V) ($\mu g\ l^{-1}$)	96	250
Arsenic (As) ($\mu g\ l^{-1}$)	< 10	50
Cadmium (Cd) ($\mu g\ l^{-1}$)	< 3	5
Chromium (Cr) ($\mu g\ l^{-1}$)	< 10	50
Lead (Pb) ($\mu g\ l^{-1}$)	< 10	50
Selenium (Se) ($\mu g\ l^{-1}$)	< 5	10
Mercury (Hg) ($\mu g\ l^{-1}$)	< 0.1	1
Asbestos ($\mu g\ l^{-1}$)	n.r.	30
DOC ($mg\ l^{-1}$)	4	30
pH	11.4	5.5 - 12.0

Caratteristiche fisiche e chimiche

Test	Standard EN	EAF 0/8 mm	EAF 8/16 mm	EAF 16/32 mm	Limestone 0/32 mm
Flakiness index (%)	EN 933-3	9.24 (FI_{20})	13.07 (FI_{20})	11.50 (FI_{20})	10.67 (FI_{20})
Shape index (%)	EN 933-4	7.62 (SI_{20})	7.67 (SI_{20})	7.63 (SI_{20})	7.02(SI_{20})
Los Angeles coefficient (%)	**EN 1097-2**	**15.10 (LA_{20})**	**13.00 (LA_{20})**	**12.44 (LA_{20})**	**23.1(LA_{25})**
Micro-Deval coefficient (%)	**EN 1097-1**	**6.3 ($M_{DE}15$)**	**6.1 ($M_{DE}15$)**	**7.0 ($M_{DE}15$)**	**13.8 ($M_{DE}15$)**
Polished stone value (%)	**EN 1097-8**	**-**	**52.9**	**61.1**	**48**
Water absorption (%)	EN 1097-6	0.63 ($WA_{24}1$)	0.60 ($WA_{24}1$)	0.59 ($WA_{24}1$)	0.47($WA_{24}1$)
Freezing and thawing resistance (%)	EN: 1367-1	3.30 (F_4)	2.30 (F_4)	2.14 (F_3)	1.16(F_1)
Sand equivalent test (%)	EN 933-8	77	-	-	68
Specific gravity (kN m^{-3})	**EN 1097-6**	**39.62**	**38.57**	**38.11**	**28.54**

The initials in ( ) are the category for each parameter described in EN 13242:2013

Test	Standard EN	Value
Water-soluble chloride salts (Mohr method) (% by mass)	EN 1744	0.002
Acid soluble sulfates (% by mass)	EN 1744-1	0.586 ($AS_{0,8}$)
Total sulfur content (% by mass)	EN 1744-1	0.108 (S_1)
Water soluble-sulfates	EN 1744-1	0.543 ($SS_{0,7}$)

SCORIE SOTTOPRODOTTO DI ACCIAIERIA NEI MISTI GRANULARI
Fenomeni di rigonfiamento

Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 8(2):103-111

Swelling Behavior of Electric Arc Furnace Aggregates for Unbound Granular Mixtures in Road Construction

Federico Autelitano[1] and Felice Giuliani[1+]

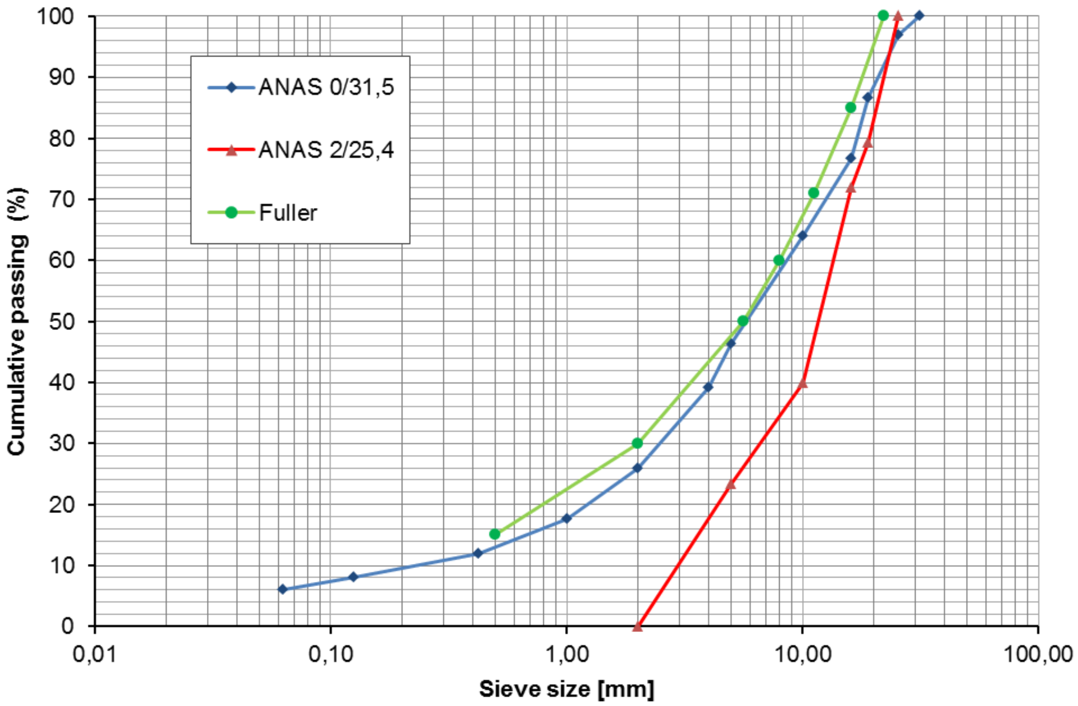
Abstract: Artificial aggregates, which result from the treatment of electric arc furnace slags (EAF aggregates), represent a very interesting technological solution to replace natural aggregates in different road construction applications. In spite of excellent mechanical properties, the swelling nature of some expansive compounds present in their mineralogy could be detrimental to volumetric stability of civil works. In light of these considerations, the main objective of this research was to analyze the volume stability of different unbound granular mixtures composed by EAF aggregates (aged and fresh) through two accelerated swelling procedures: water-bath swelling test (ASTM D4792/D4792M-13) and steam test (EN 1744-1).

The results demonstrated how the expansive developmental process follows, in general, three different progressive phases. Both expansion development and final swelling extent were a function of preliminary exposition to aging treatment and different physical factors, such as particle size, grain size distribution, and degree of compaction. The expansive behavior was more evident for fresh slag aggregates, which did not undergo any type of stabilization procedure. Specifically, the residual voids content, which is in close correlation with the degree of compaction, can be considered the main factor affecting swelling ratio. All specimens analyzed, however, showed appropriate expansion values according to ASTM and EN standard requirements.

DOI: 10.6135/ijprt.org.tw/2015.8(2).103

Key words: EAF aggregates; Swelling; Unbound mixtures.

Miscele



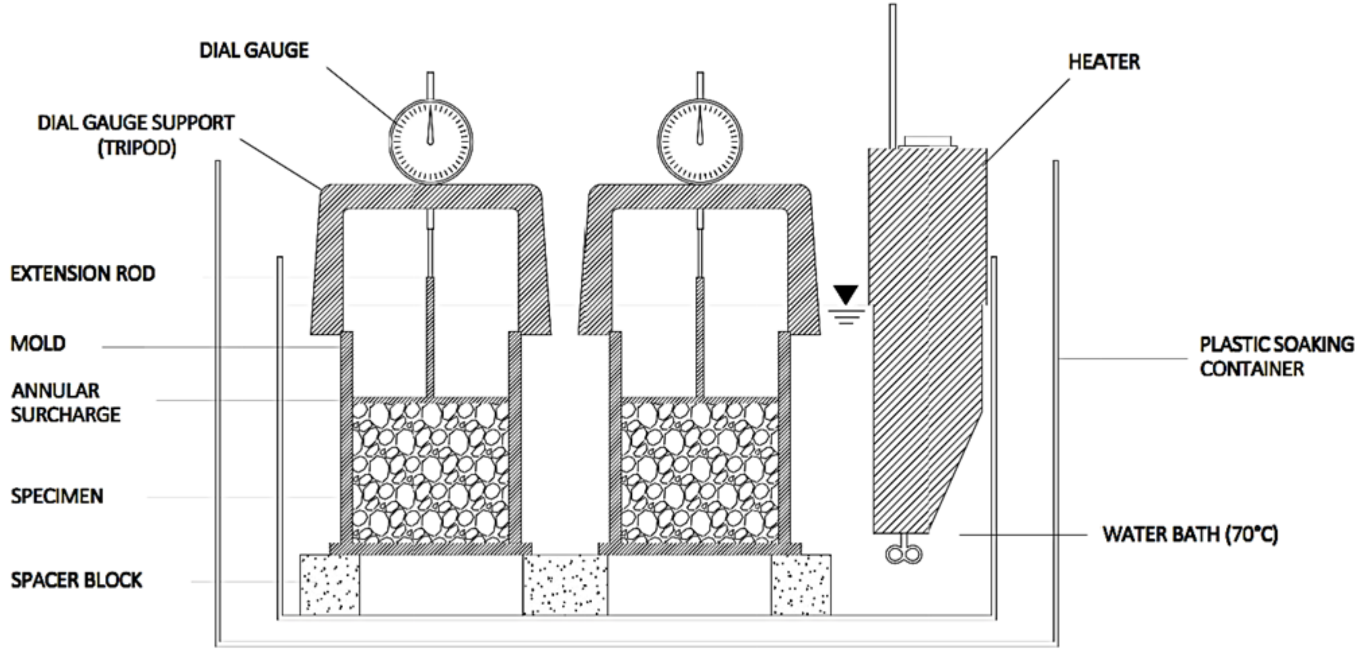
Curva granulometrica: ANAS (1) vs Fuller (2)

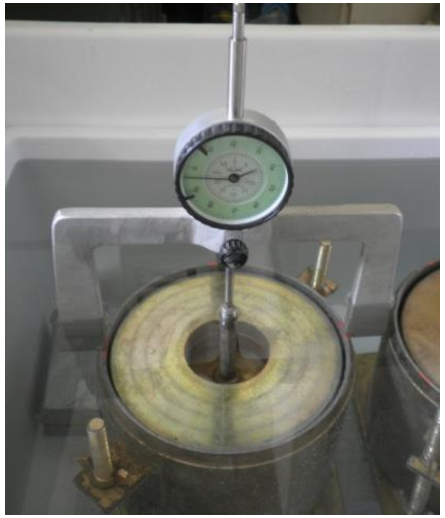
Series	Composition	Grain-size distribution (mm)	Compaction	Voids content (%)
A1P*	Aged EAF	ANAS (0/31.5)	Proctor	22.97
A1'P*	Aged EAF	ANAS (0/31.5)	Proctor	23.76
F1P*	Fresh EAF	ANAS (0/31.5)	Proctor	19.97
F_30*P	30% Fresh EAF 70% Limestone	ANAS (0/31.5)	Proctor	20.52
F_60*P	60% Fresh EAF 40% Limestone	ANAS (0/31.5)	Proctor	20.61
A1P	Aged EAF	ANAS (2/25.4)	Proctor	35.64
A1V	Aged EAF	ANAS (2/25.4)	Vibrating table	40.56
A2P	Aged EAF	Fuller (0/22)	Proctor	27.51
A2V	Aged EAF	Fuller (0/22)	Vibrating table	37.40
A5/8V	Aged EAF	5/8	Vibrating table	45.43
A8/16V	Aged EAF	8/16	Vibrating table	40.12
A8/16P	Aged EAF	8/16	Proctor	36.88
A16/19V	Aged EAF	16/19	Vibrating table	46.30
A19/25.4V	Aged EAF	19/25.4	Vibrating table	45.43
F1P	Fresh EAF	ANAS (2/25.4)	Proctor	32.09
F1V	Fresh EAF	ANAS (2/25,4)	Vibrating table	43.78
F2P	Fresh EAF	Fuller (0/22)	Proctor	27.61
F2V	Fresh EAF	Fuller (0/22)	Vibrating table	36.79

PROCTOR Modificata (EN 13286-2): 4.5 kg, 56 colpi (da 45.7 cm), 5 strati

VIBRATING PLATE (EN 1744-1): 48 ± 3 Hz, 6 min

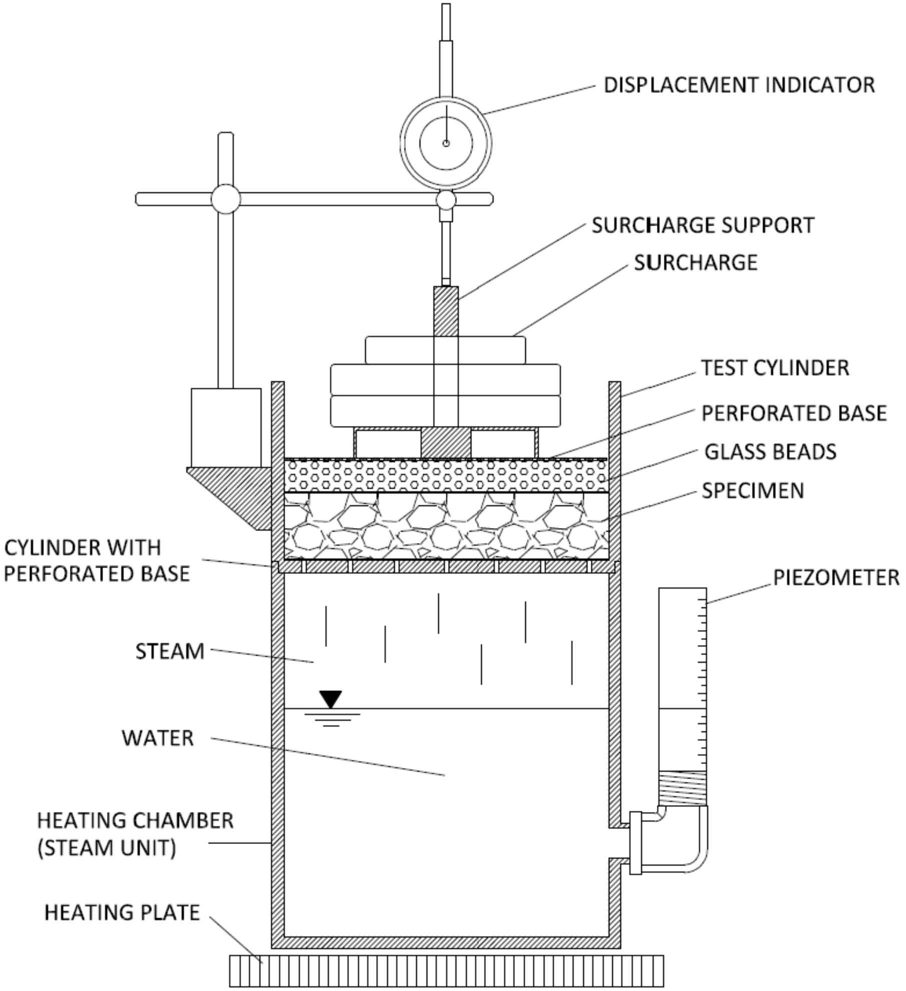
Water-bath Swelling Test (D4792/D4792M-13)





- 7 giorni (168 h)
- 4.54 kg
- 70 °C

European Steam Test (EN 1744-1)



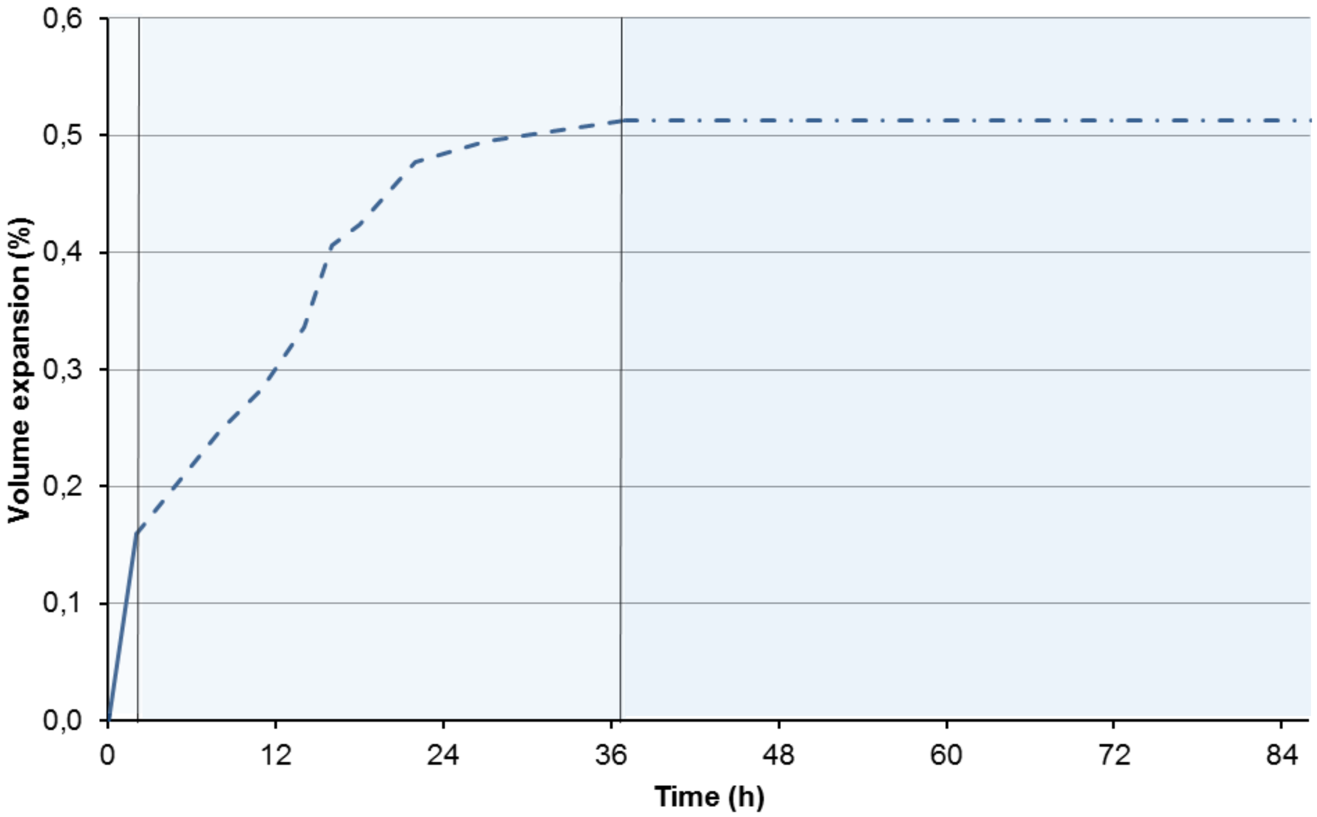
7 giorni (168 h)

6.51 kg

100 °C

Meccanismi di idratazione CaO e MgO

F1P - European Steam Test



Espansione in 3 fasi

Idratazione di CaO rapida
(fasi I e II)

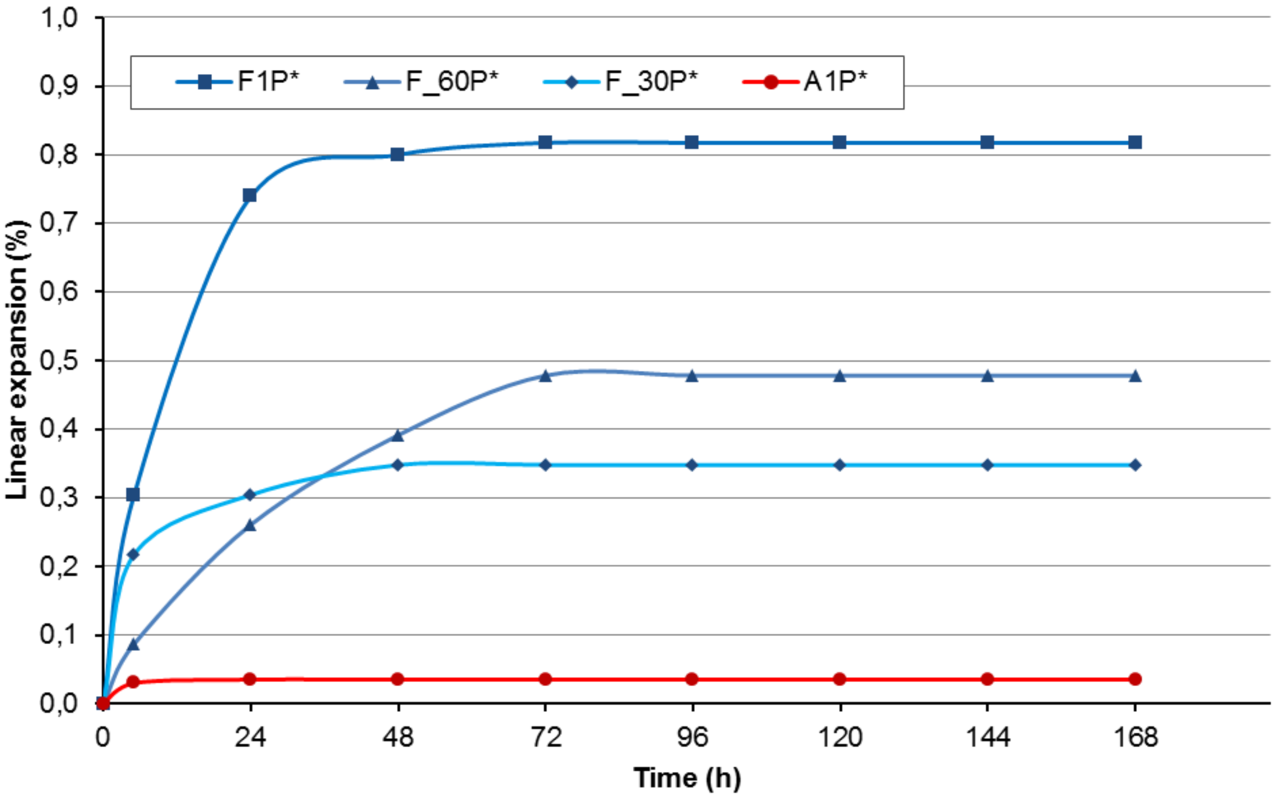
Bassi tenori di MgO (2.15%)
(stabilizzazione in 36 h)

Steam test: Espansioni maggiori
(No effetti dissoluzione)

LIMITI
< 5% steam test
< 0.5% water-bath

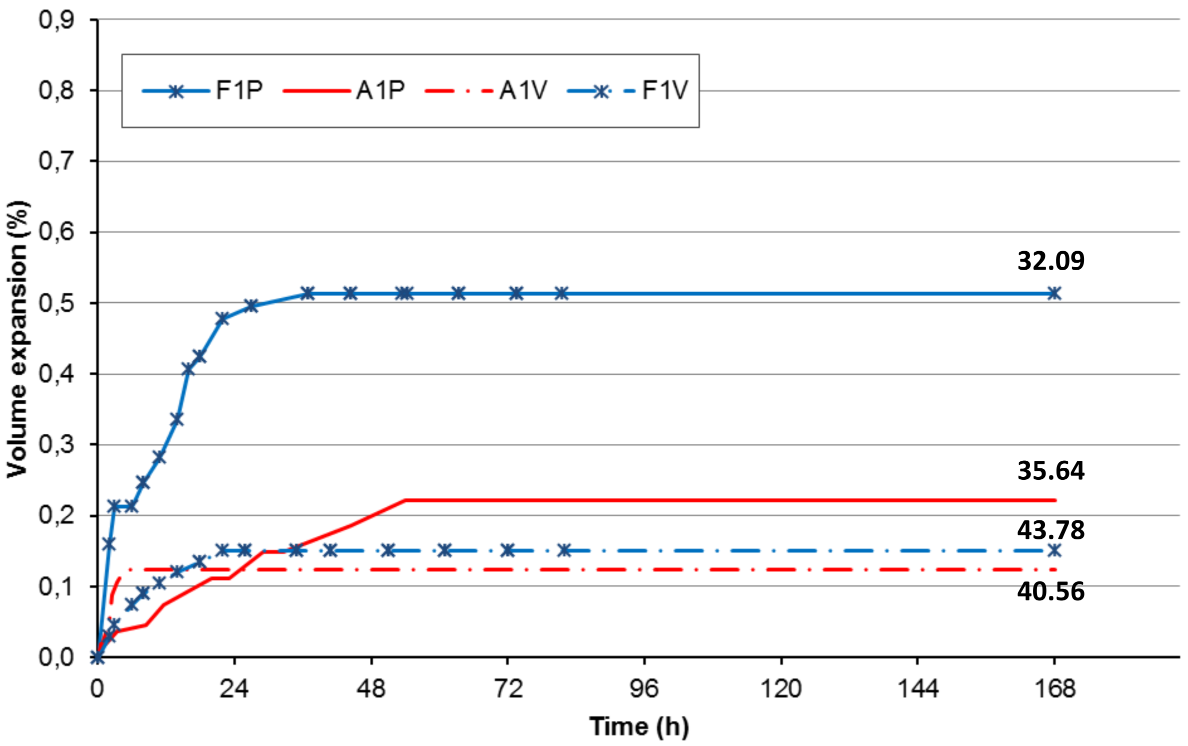
Water-bath Swelling Test*

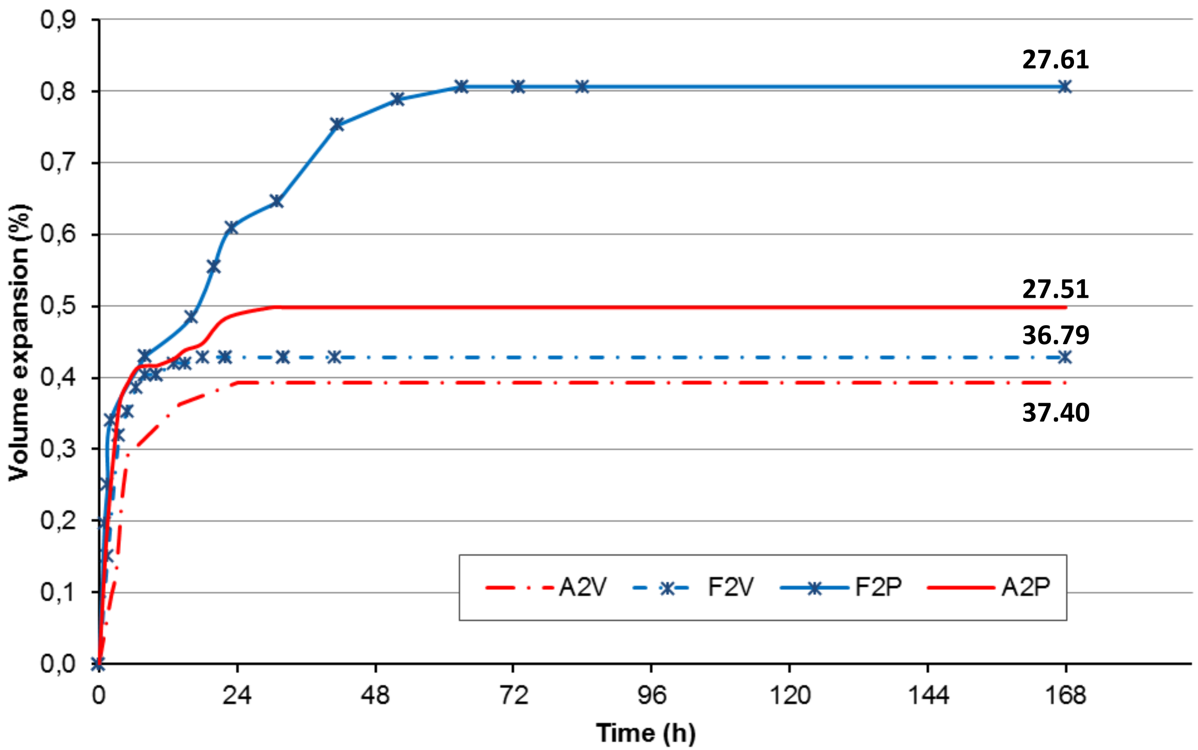
Procedura modificata
(Rimozione del sovraccarico)



Risultati: Espansione volumetrica

European Steam Test

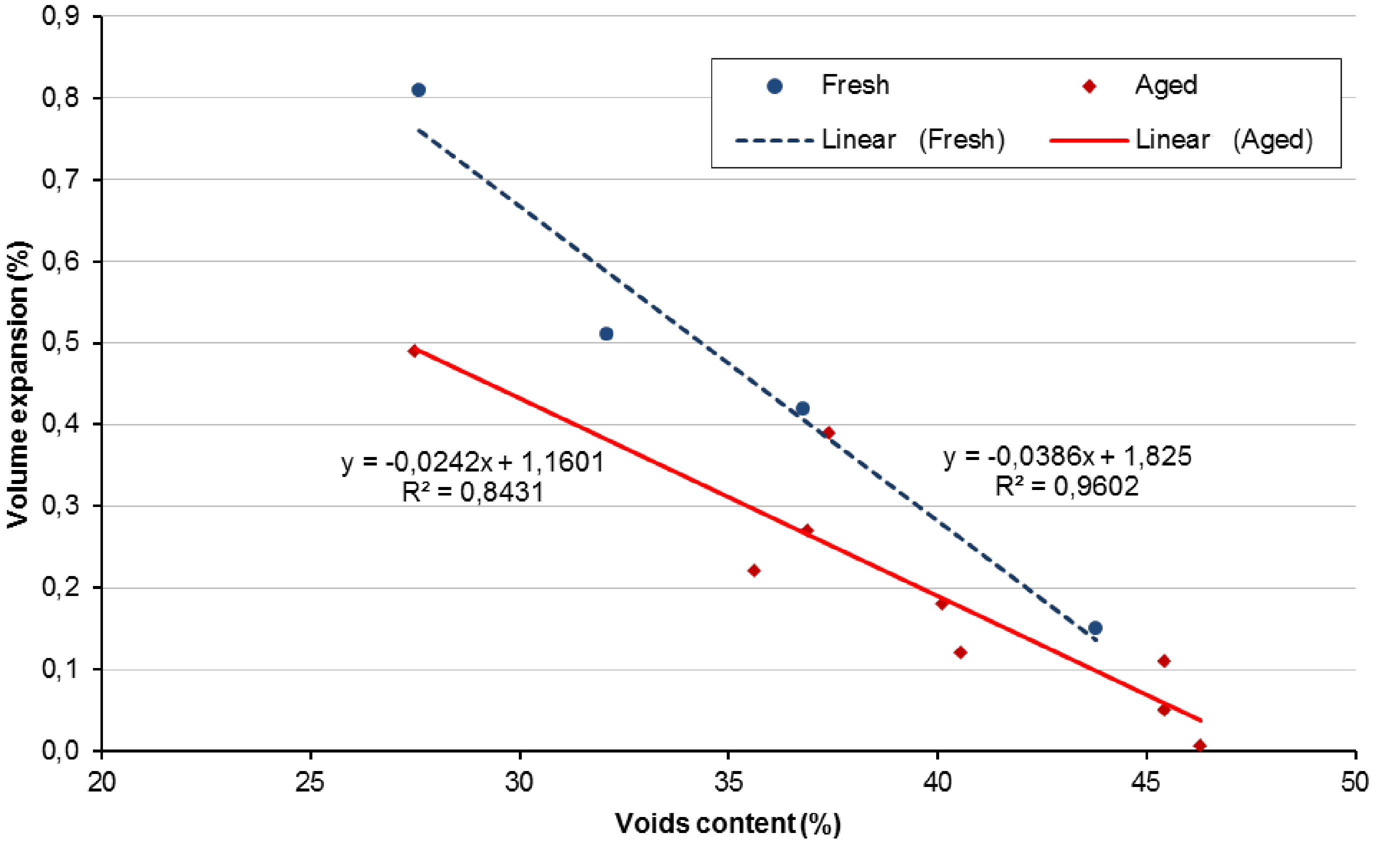




Modalità di compattazione: **Proctor (P)** vs Tavola vibrante (V)

Curva granulometrica: ANAS (1) vs **Fuller (2)**

Influenza del contenuto di vuoti



SCORIE SOTTOPRODOTTO DI ACCIAIERIA NEI MISTI CEMENTATI
Proprietà fisico-meccaniche e di durabilità

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ELSEVIER

Electric arc furnace slags in cement-treated materials for road construction: Mechanical and durability properties

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H I G H L I G H T S

- The aged EAF slags represented suitable aggregates for CTMs.
- Increasing the EAF aggregates content, CTMs developed lower degree of compaction but higher ITS.
- CTMs containing only EAF aggregates showed poor durability performance.
- EAF aggregates partial replacement (30–60%) of natural aggregates produced suitable and durable CTMs.

A R T I C L E I N F O

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Steel slags
EAF aggregates
Road construction
Pavement engineering
Gyratory compactor
Durability

A B S T R A C T

Electric arc furnace (EAF) slags are by-products of a widespread steelmaking process. The recycling of these materials as artificial aggregates in different road applications is a well established practice, which has allowed to reduce the consumption of natural resources and to minimize waste production and costs of landfilling. However, these aggregates are still underutilized in cement-treated materials (CTMs), which consist of mixtures of aggregates blended with small amounts of cement and water that harden after compaction to form a strong paving material. In the light of these considerations, different cement-treated materials, each containing different percentages of natural and artificial aggregates were analyzed. After a preliminary characterization of chemical, physical and durability properties of EAF slag aggregates, a mix design procedure based on both moisture-density approach (gyratory compactor) and mechanical testing (unconfined compression test and indirect tensile test) was performed to identify the optimum cement and water content of CTMs. The design mixtures were then subjected to 5 different accelerated aging procedures in order to study the influence of some factors (temperature, pressure and humidity) on the durability of the cement-treated materials. The results highlighted how the EAF

Misto cementato

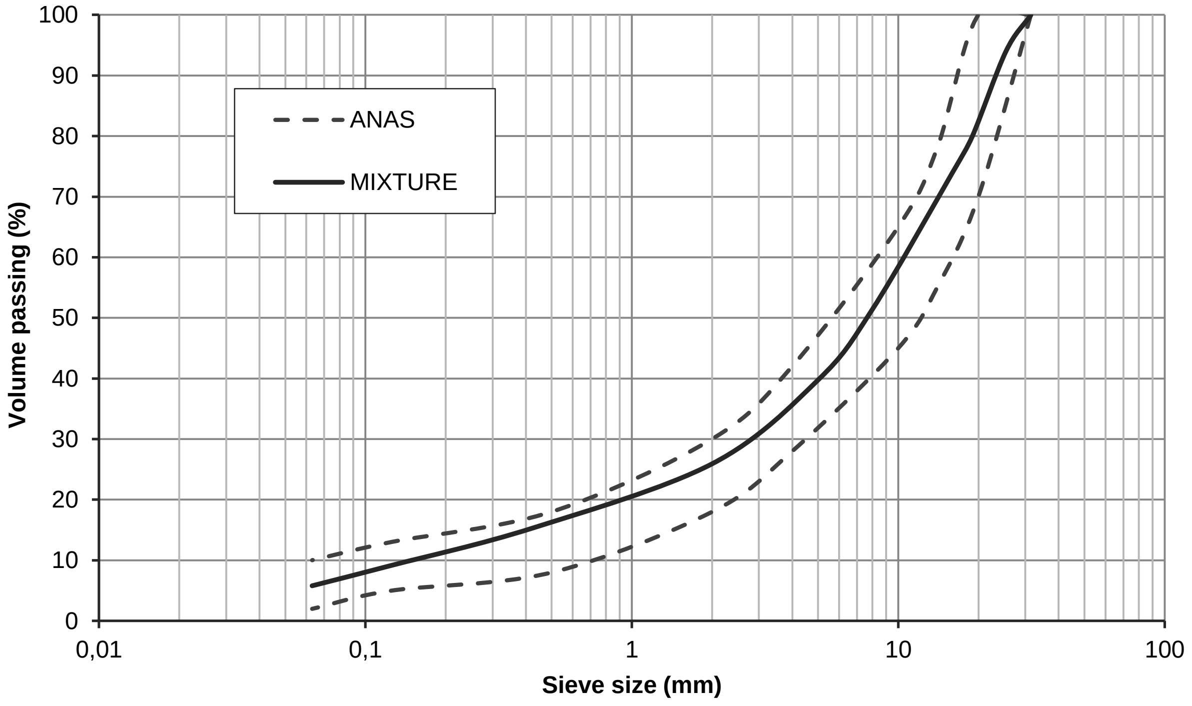
Requisiti internazionali

Country	Cement content (%)	Requirement
		UCS at 7-days curing time (MPa)
Australia	3-8	> 3
Brazil	~4	> 3.5
China	> 4% (Road-mix method) > 5% (Central-plant mixing)	> 2 (Base) > 4 (Subbase)
Spain	3.5-6%	4.5-6
UK	2-5%	2.5-4.5 (CM1) 4.5-7.5 (CM2)
USA	3-10%	3.5-6.9 (under PCC) 5.2-6.9 (under HMA)

Country	Cement content (%)	Requirement	
		UCS at 7-days (MPa)	ITS at 7-days (MPa)
Italy	2-4%	2.5-5.5 (Gyratory compactor) 2.5-4.5 (Proctor hammer)	0.32-0.60 (Gyratory compactor) > 0.25 (Proctor hammer)
South Africa	1.5-3% 3-5%	1.5-3.0 0.75-1.5	> 0.25 > 0.20
		UCS at 90-days (MPa)	TS* at 90-days (MPa)
France	2.5-4%	5-10	1

* TS = Tensile strength

Miscele



S 96% EAF

SL 60% EAF (5/31.5 mm)

LS 30% EAF (16/31.5 mm)

L 100% Calcare

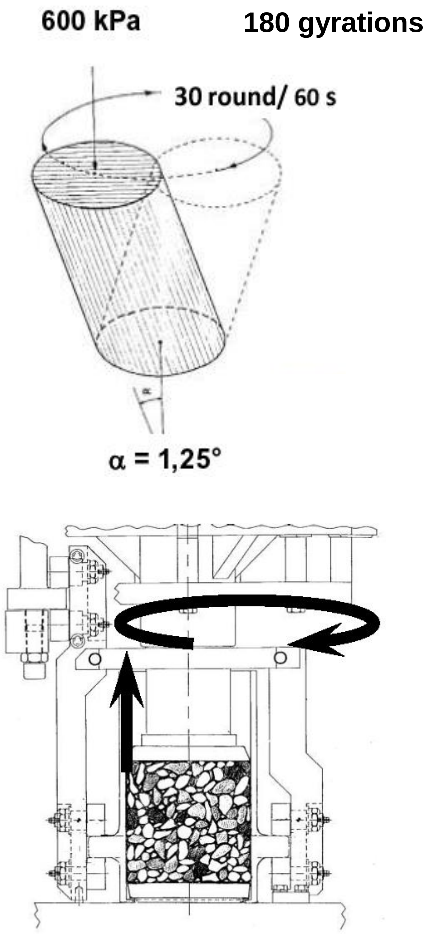
Filler calcareo

Mix-design volumetrico – Coefficienti correttivi

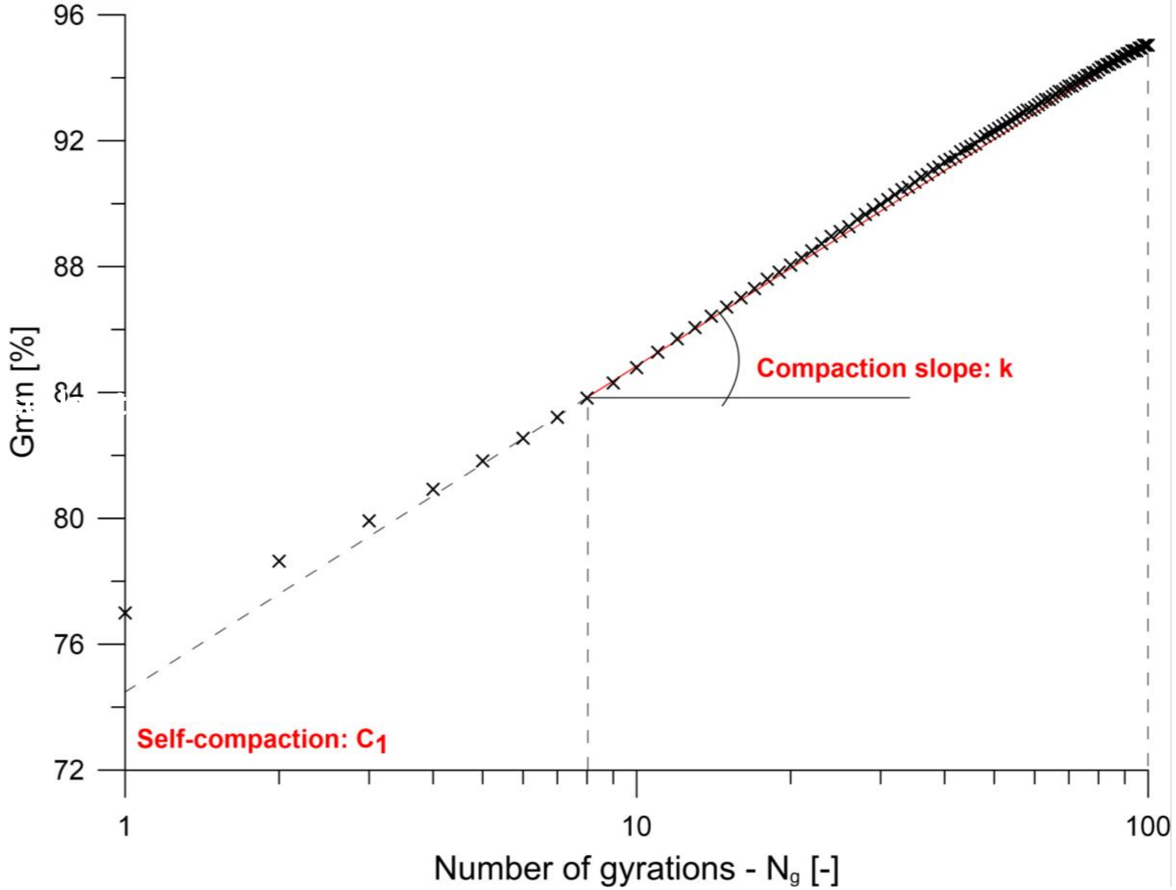
Mixture	EAF (m/m %)	Limestone (m/m %)	ρ_M (kg m^{-3})	$\alpha_M = \frac{\rho_L}{\rho_M}$	c_{nom} (m/m %)	c_{eff} (v/v %)	w_{nom} (m/m %)	w_{eff} (v/v %)
L	0	100	2753	1.000	2	2	5	5
					3	3	6	6
					4	4	7	7
LS	30	70	3141	0.877	2	1.8	5	4.4
					3	2.6	6	5.3
					4	3.5	7	6.1
SL	60	40	3518	0.783	2	1.6	5	3.9
					3	2.4	6	4.7
					4	3.1	7	5.5
S	94	6	3824	0.720	2	1.4	5	3.6
					3	2.2	6	4.3
					4	2.9	7	5.0

Pressa giratoria: grado di compattazione e lavorabilità

EN 12697-31



$$\%G_{mm} = C_1 + k \cdot Log(N_g)$$

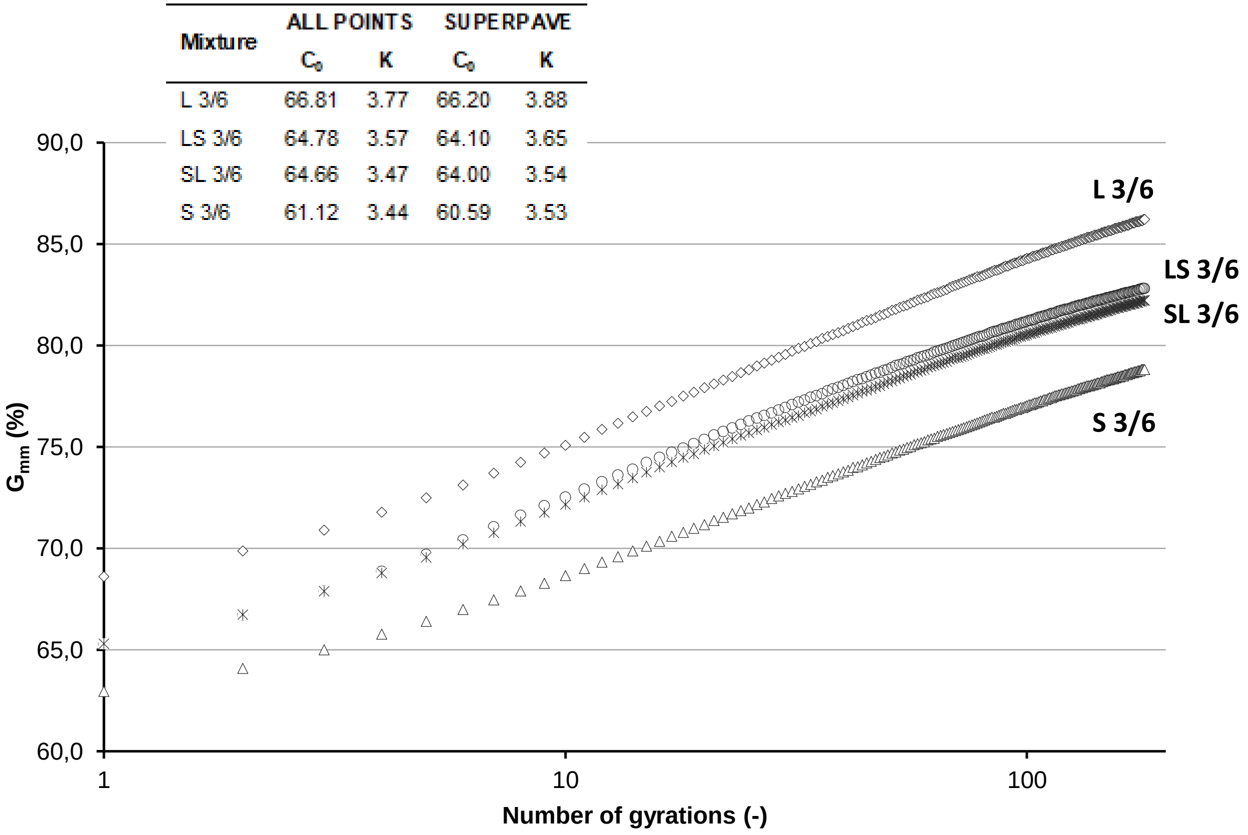


Risultati: Scelta della miscela ottima

Pressa giratoria: grado di compattazione e lavorabilità

G_{mm}% - Densità massima teorica

c_{nom} (m/m %)	w_{nom} (m/m %)	Mixture L	LS	SL	S
2	5	84.57	82.32	80.22	75.78
2	6	85.62	82.50	81.28	76.01
2	7	86.86	82.50	83.26	77.78
3	5	83.14	82.08	80.27	76.18
3	6	87.83	83.46	83.77	78.91
3	7	87.19	83.24	82.22	78.75
4	5	85.51	82.40	80.59	77.66
4	6	87.25	83.35	82.01	77.98
4	7	87.63	83.40	83.64	78.83



Resistenza a compressione (EN 13286-41)

7 giorni

23 °C

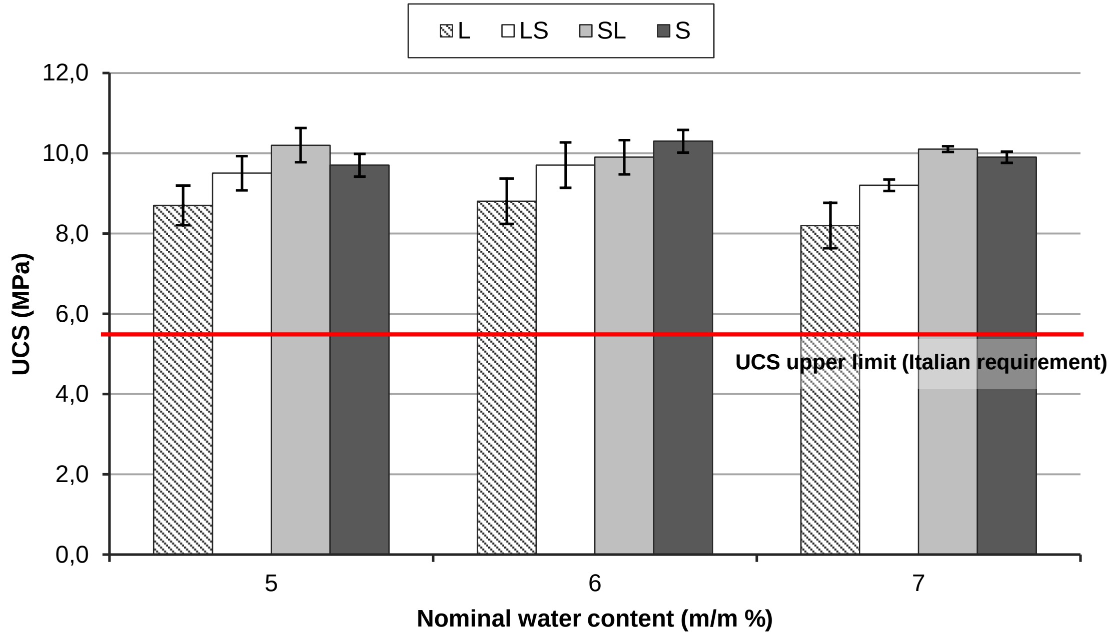
Resistenza a trazione indiretta (EN 13286-42)

3, 7, 14, 21 giorni

23 °C

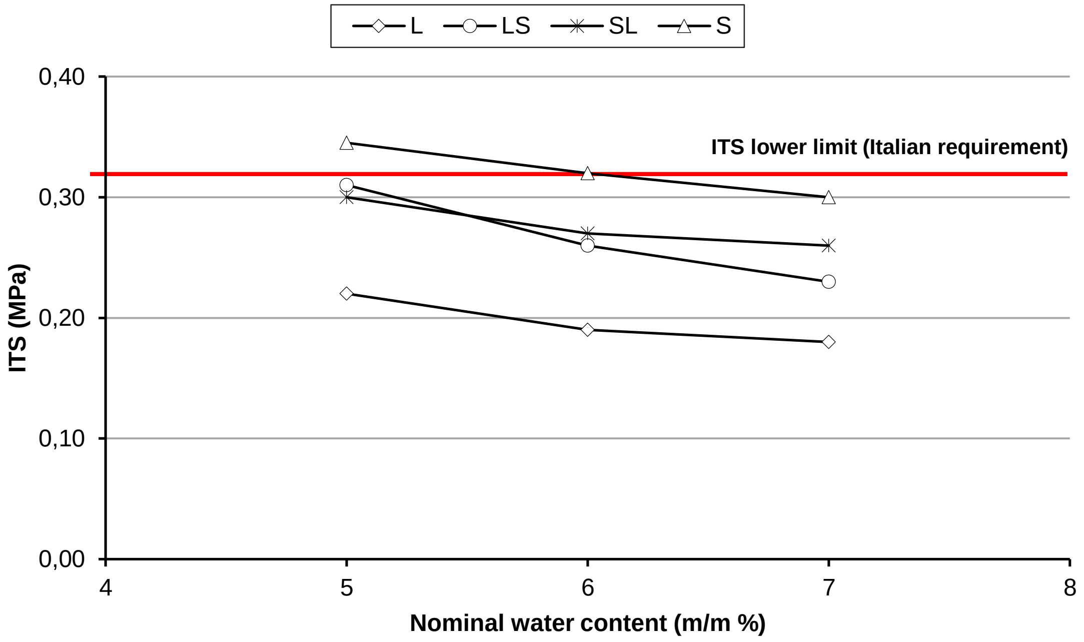
Resistenza a compressione (EN 13286-41)

Cemento: 4%



Resistenza a trazione indiretta (EN 13286-42)

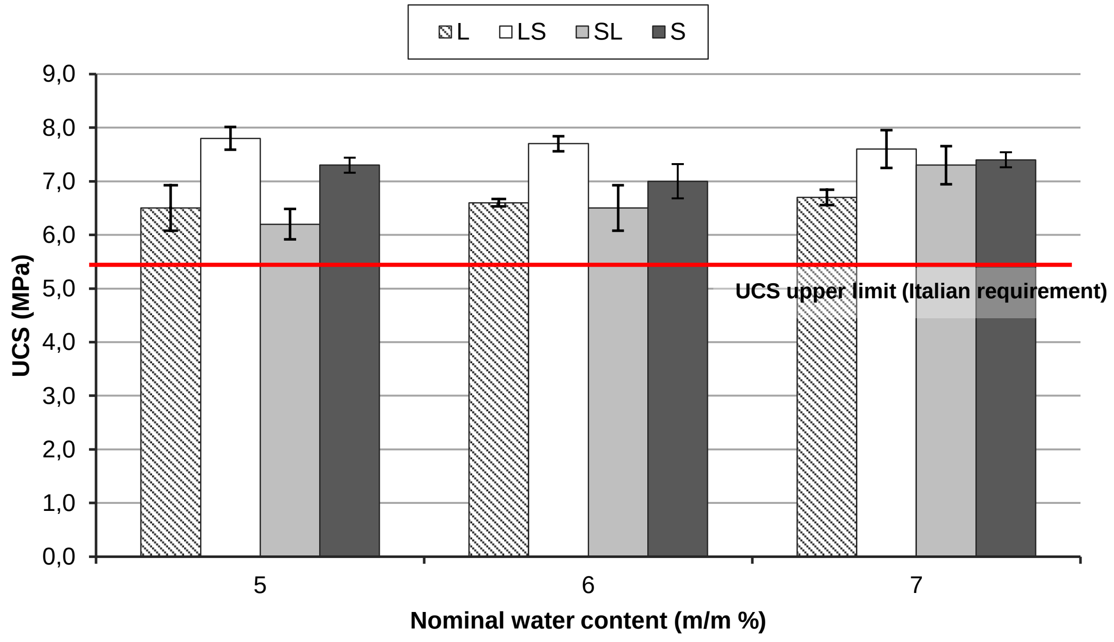
Cemento: 2%



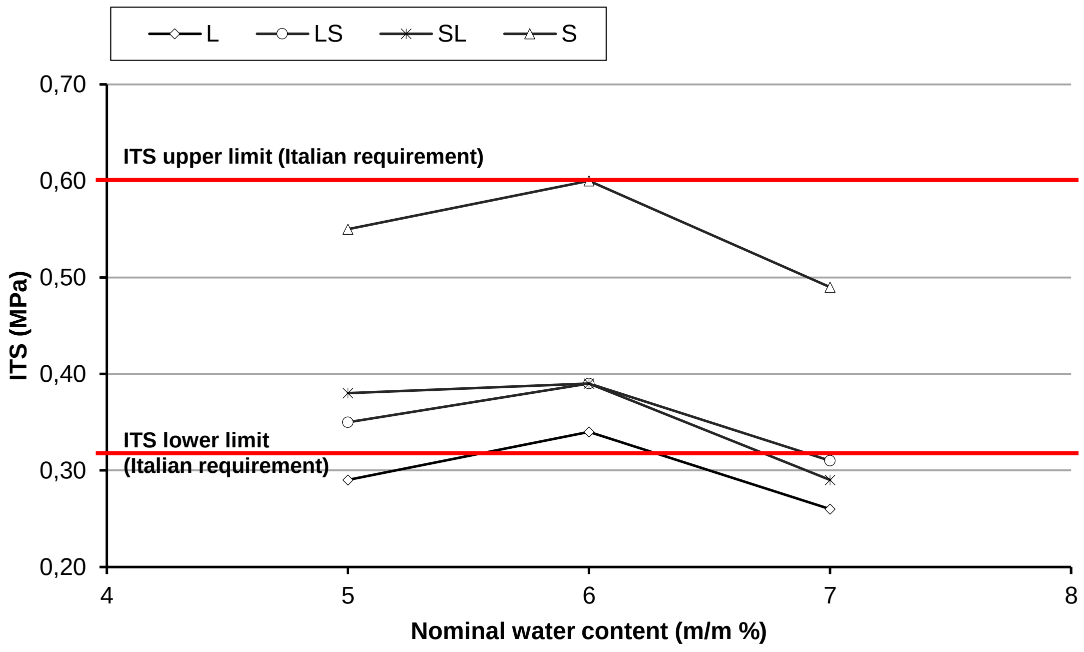
Metodologia: Scelta della miscela ottima

Resistenza a compressione (EN 13286-41)

Cemento: 3%



Resistenza a trazione indiretta (EN 13286-42)



Metodologia: Durabilità

Sollecitazione fisico-chimica «estrema»

Test su provini condizionati 28 giorni (T = 23 °C, UR = 55 %)

- Aspetto
- Variazione volumetrica
- Perdita di resistenza meccanica (trazione indiretta)

Bagno termostatico

70 °C per 20 giorni
Asciugatura superficiale – Raffreddamento a 25 °C per 2 h

Alta pressione

112 ° C alla pressione di 155 kPa (1.55 bar) per 3 h

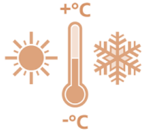
Procedure cicliche

Cicli di gelo e disgelo (20)

-19 °C per 18 h / 4 °C per 6 h
(Campioni saturi in contenitori a tenuta)

Cicli di bagnatura e asciugatura (20)

23°C per 18 h in acqua / 110 °C per 6 h in forno



Shock termico (2 cicli)

112 ° C alla pressione di 155 kPa per 3 h / -19 °C per 18 h

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Bagno termostatico

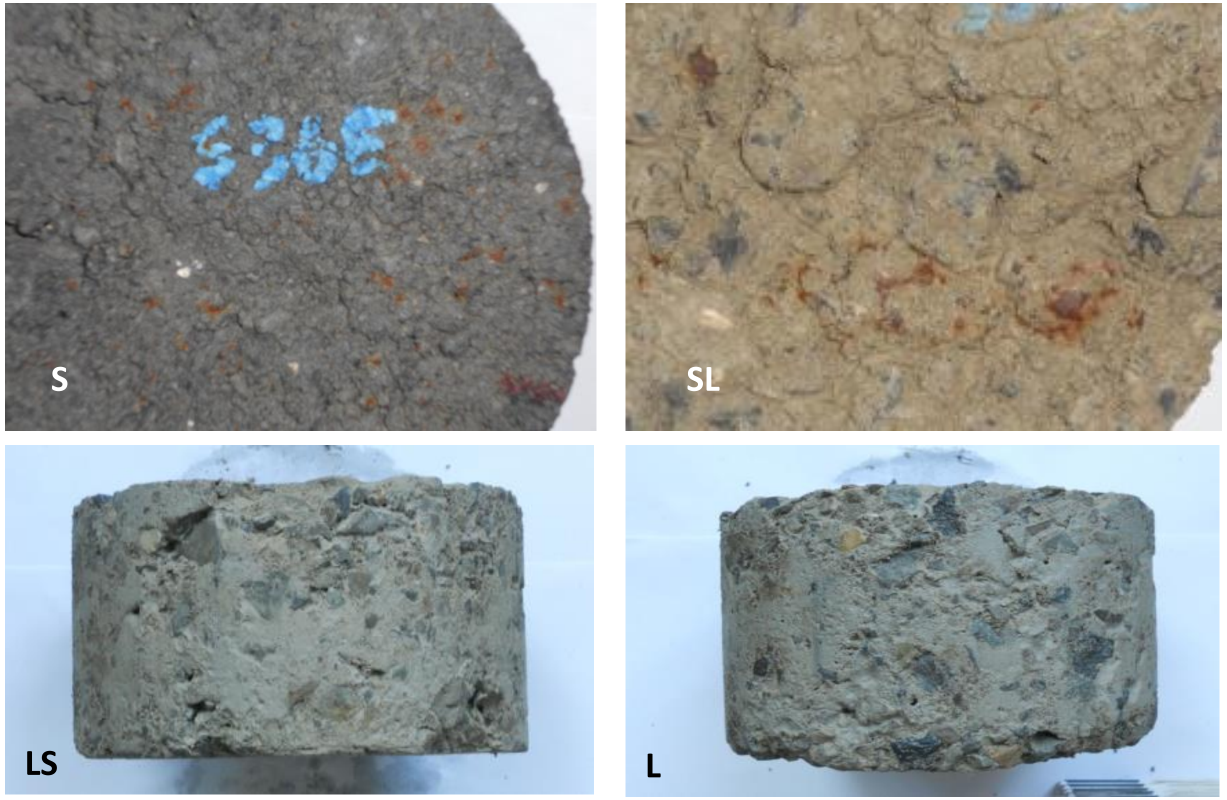
Mixture	Volume variation (%)	Indirect tensile strength (ITS) (MPa)		Strength variation (%)	Superficial appearance
		Before	After		
L	0.26	0.34	0.45	+32.35	Good
LS	0.24	0.48	0.53	+10.42	Slight oxidization
SL	0.40	0.48	0.50	+4.16	Slight oxidization
S	0.91	0.62	0.37	-40.32	Slight oxidization Detachment of coarse aggregates

Alta pressione

Mixture	Volume variation (%)	Indirect tensile strength (ITS) (MPa)		Strength variation (%)	Superficial appearance
		Before	After		
L	0.40	0.34	0.26	-23.53	Good
LS	0.47	0.48	0.29	-39.58	Good
SL	0.32	0.48	0.31	-35.42	Good
S	0.46	0.62	0.30	-51.61	Slight oxidization

Cicli di bagnatura e asciugatura (20)

Mixture	Volume variation (%)	Indirect tensile strength (ITS) (MPa)		Strength variation (%)	Superficial appearance
		Before	After		
L	0.27	0.34	0.25	-26.47	Stripping Detachment of coarse aggregates
LS	0.35	0.48	0.32	-33.33	Stripping Detachment of coarse aggregates
SL	0.38	0.48	0.26	-45.83	Slight oxidization
S	0.75	0.62	0.32	-48.39	Slight oxidization



Cicli di gelo e disgelo (20)

Mixture	Volume variation (%)	Indirect tensile strength (ITS) (MPa)		Strength variation (%)	Superficial appearance
		Before	After		
L	1.07	0.34	0.13	-61.76	Mortar flaking
LS	2.22	0.48	0.13	-72.92	Mortar flaking
SL	n.a*	0.48	n.a*	n.a*	Two specimens almost completely destroyed
S	3.29	0.62	0.14	-77.42	Significant internal oxidization Detachment of coarse aggregates

Shock termico (2 cicli)

Mixture	Volume variation (%)	Indirect tensile strength (ITS) (MPa)		Strength variation (%)	Superficial appearance
		Before	After		
L	-0.67	0.34	0.21	-38.24	Stripping
LS	0.02	0.48	0.24	-50.00	Stripping
SL	0.38	0.48	0.31	-35.42	Rather good
S	0.62	0.62	0.12	-80.65	Superficial cracking


S


L