Lecture Notes in Civil Engineering

Alper Ilki
Derya Çavunt
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Editors

Building for the Future: Durable, Sustainable, Resilient

Proceedings of the *fib* Symposium 2023 – Volume 1

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Preface

Concrete is a widely used material in the construction industry due to its versatility, strength, and durability. However, the production of concrete has a significant impact on the environment, contributing to carbon emissions, resource depletion, and waste generation. This has led to an increasing need to address sustainability concerns in the construction industry.

As the world population grows and the impact of climate change becomes more severe, the demand for sustainable buildings has also increased. Sustainable buildings minimize their environmental impact by reducing resource consumption, minimizing waste generation, and improving energy efficiency. Moreover, durable and resilient structures are crucial aspects of sustainable construction. Structures that can withstand the test of time and natural disasters reduce the need for frequent repairs and replacements, thereby reducing the resources needed for ongoing maintenance.

Sustainable structures also provide long-term financial benefits by reducing operational costs. This is achieved through measures such as energy-efficient designs and the use of sustainable materials. In this aspect, it is essential for the construction industry to prioritize sustainability to ensure a better future for the world.

In order to address the next steps in the construction industry, the *fib* International Symposium 2023, "Building for the Future: Durable, Sustainable, Resilient," was held in Istanbul, Turkey on June 5–7, 2023, as an official symposium of the International Federation for Structural Concrete (*fib*), by the contribution of International Federation for Structural Concrete Turkey Branch (*fib* Turkey), Istanbul Technical University (ITU), and the Turkish Earthquake Foundation (TEF).

The primary goal of the symposium was to provide a platform for scientists, engineers, industrial partners, and practitioners to present and discuss recent advances, state of the practice, and future perspectives in terms of durability, sustainability, and resiliency in civil engineering. The symposium covered topics related to concrete and innovative materials, structural performance and design, construction methods and management, and outstanding structures.

We are pleased to present the proceedings book of the *fib* International Symposium 2023 published by Springer, which consists of two volumes and includes 372 papers from 55 countries worldwide. All papers submitted to the symposium underwent a rigorous review process by the members of the International Scientific Committee. We would like to thank all the authors for their valuable contributions, as well as the members of the International Scientific Committee for their hard work and dedication to ensuring the quality of the papers. In the symposium, a total of 412 presentations were made, including 6 keynote and 14 invited theme lecturer presentations. We would like to extend our sincere thanks and appreciation to all the speakers, with special thanks to the keynote and invited speakers for their invaluable contributions.

We would like to express our sincere thanks to the members of the organization committee of the symposium, as well as to Prof. Dr. Stephen J. Foster, the president of

the *fib*, Dr. Akio Kasuga, previous president of the *fib*, Dr. David Fernández-Ordoñez, co-chair of the symposium, and secretary general of the *fib*, Ali Karahan, co-chair of the symposium, and Marie Reymond, communications and events specialist of the *fib*, for their support. Additionally, we are grateful for the support of ITU, TEF, the Scientific and Technological Research Council of Turkey (TUBITAK), *fib* Turkey, and the sponsors.

We would also like to extend our appreciation to the M.Sc./Ph.D. students who volunteered their time and efforts to ensure the success of the symposium.

We believe that the *fib* International Symposium 2023-Istanbul was a productive and unforgettable experience for all participants.

Sincerely,

June 2023

Alper Ilki
Derya Çavunt
Yavuz Selim Çavunt

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Qian Qian Yu, China
Nilüfer Özyurt Zihnioğlu, Turkey

Keynote Lecturers

Brahim Benmokrane
Brahim Benmokrane is one of the world's top in the field of structural concrete internally reinforced with fiber reinforced polymer (FRP) reinforcement. His research has significantly influenced the development of concrete structures reinforced with FRP bars, building codes, design specifications, and its practical use in North America and beyond. He has pioneered the development of related specifications and industry standards for using these new structural materials. His recognition as a leader in his field is not limited to his colleagues in academia but extends to industry, professional societies, and public agencies. His contributions go beyond his cutting-edge research to include leadership and involvement in developing international design codes and specifications for engineers and users. His research and professional services have been recognized with several awards. Some of his more note-worthy awards have come from ACI, CSCE, CSA, IIFC, NSERC, and the Royal Society of Canada (Fellow of Academy of Science). He is one of the scientists most cited in the world in the field (17,400+ Citations, h-index = 71, by Google Scholar). Professor Benmokrane holds the Tier–1 Canada Research Chair in Advanced Composite Materials for Civil Structures and the NSERC-Alliance Industrial Research Chair in Innovative FRP Reinforcement for Sustainable Concrete Infrastructures at the Department of Civil and Building Engineering at the University of Sherbrooke (Sherbrooke, QC, Canada). He currently leads a research group of 32 and has trained 170 researchers. He founded the world's largest research lab on FRP reinforcing bars for concrete structures at the University of Sherbrooke, which helps the industry in developing and receiving approval for new construction materials requiring certification under International Codes and Standards. Over the last 25 years, Professor Benmokrane has worked with Canadian and international engineering firms and government departments and counts many world firsts to his credit in terms of bridges, parking facilities, water treatment plants, and tunnels. He has acted as a consultant on major national

and international projects using FRP bars, such as the Nipigon Cable Stayed Bridge on the Trans-Canada Highway (northwestern Ontario, Canada), Highway 40 & Champlain Bridge (Montreal, Canada), TTC Subway North Tunnels (Highway 407) (Toronto, Canada), Port of Tanger Med II (Morocco), and Port of Miami Tunnel (FL, USA).

Konrad Bergmeister

Konrad Bergmeister studied Civil Engineering, Univ. of Innsbruck (Austria)—Rural Architecture, History of Art, Philosophy, Univ. of Innsbruck (Austria)—Manufacturing systems, University of Clarkson, New York (USA), Doctoral degree in Philosophy, University of Innsbruck Doctoral degree in Technical Sciences, University of Innsbruck Doctoral degree in Macro-Economics, European University of Bratislava-Vienna 1990; Konrad Bergmeister is the founding of the civil engineering company Bergmeister. In 1993, Konrad Bergmeister is a professor at the Institute of Structural Engineering, Vienna. From 1999–2006, Konrad Bergmeister is chief engineer and technical director of the Brenner highway. From 2006–2019, Konrad Bergmeister is CEO of the Brenner Base Tunnel (world longest tunnel). In 1999, Konrad Bergmeister is the chief editor of the journal “Beton- und Stahlbetonbau” (Concrete and Reinforced Concrete Structures). In 2003, Konrad Bergmeister is the editor of the Betonkalender with Fingerloos, Wörner.

Member of IABSE and various national committees on structural engineering

Member, national delegate, and chair of fib commissions

Full member of the Berlin-Brandenburg Academy of Sciences and Humanities

Full member of the National German Academy of Sciences Leopoldina

Full member of the European Academy of Science and Art

Honorary Professor of the Zhejiang Guangsha College of Technology, China

700 scientific publications, 5 books, and editor of 20 books.

Omer Guzel

He graduated from Istanbul Technical University Faculty of Civil Engineering in 1995. After 2 years, he completed his master's degree at Istanbul Technical University, Department of Structural Engineering. He was in charge of the Structural Design Department for 18 years at Yapı Merkezi, which he entered in 1998. He worked in bridge, railway, highway, earthquake, and building engineering and designed many reinforced concrete, prefabricated, steel, prestressed, and underground structures. He worked at the manager level in many multi-disciplinary, multi-company international projects of various sizes. He has been working as a member of the Executive Committee in the 1915 Çanakkale Bridge and Highway Project since 2017.

He has been the deputy general manager at Yapı Merkezi since 2020. He is also a board member at Freysaş, Çanakkale Motorway and Bridge Construction Investment and Operation Inc., and the Turkish Constructional Steelwork Association. He is married and has a child.

Karen Scrivener

Karen Scrivener has been a professor and director of the Laboratory of Construction Materials in the Department of Materials of EPFL (Ecole Polytechnique Federale de Lausanne for the last 20 years. She is a fellow of the UK Royal Academy of Engineering and the author of over 200 journal papers. Her research focuses on understanding the chemistry and microstructure of cement-based materials and improving their sustainability. In 2008, she came up with the idea for LC3 cement; this material has the potential to cut CO2 emissions related to cement by more than 400 million tons a year. She received her bachelor's degree in Materials Science from the University of Cambridge in 1979 and her Ph.D. from Imperial College London in 1984.

Xiangyu Wang
Professor Xiangyu Wang is affiliated with School of Design and Built Environment, Curtin University, Australia. He was the founder and the inaugural chair of the Curtin Advanced Technology Research and Innovation Alliance. He has been involved in the organization of several international conferences including the honorary chair of the Conference on Innovative Production and Construction (IPC). He has published close to 400 journal articles where over 20 articles are ESI top 1% highly cited papers and nearly 10 articles are hot papers (top 0.1%). His Web of Science overall citation is close to 10,000.

Nilufer Ozyurt Zihnioglu
Dr. Nilüfer Özyurt Zihnioğlu is a professor of Construction Materials in Civil Engineering Department of Boğaziçi University, Istanbul/Turkey. She received her M.S. and Ph.D. degrees from Istanbul Technical University. She spent three years at Center for Advanced Cement-Based Materials of Northwestern University as a pre-doctoral fellow during her Ph.D. studies. She was awarded several grants during her Ph.D. including fellowships from Northwestern University, TUBITAK, and Istanbul Technical University. Dr. Özyurt has been serving as the director of Construction Materials Laboratory of Civil Engineering Department for more than ten years. Her research focuses on sustainable cement-based materials, green concrete pavements, durability of seawater-mixed concretes, fiber dispersion, and concrete under elevated temperatures. She has authored and co-authored many research papers on sustainable cement-based materials with more than 1500 citations and also serves for different technical committees of FIB and RILEM for producing cement-based materials with increased sustainability.

Invited-Theme Lecturers

Yilmaz Akkaya

Prof. Dr. Yılmaz Akkaya is a professor at the Civil Engineering Faculty of Istanbul Technical University, Turkey. He received his Ph.D. degree from Northwestern University in Illinois, USA, in 2000. He worked in construction projects as a Site Construction Chief and as a site quality control engineer after he received his B.Sc. in 1991. He received his M.Sc. from ITU in 1995. He worked as a research associate at Northwestern University during 2001–2003. He started working as an assistant professor at ITU in 2004 and as an associate professor in 2005. He was the general coordinator of Double Degree Programs and Dean of International Education at ITU between 2010–2020. He was the founder and director of the Marmaray Project Laboratory and then the Infrastructure Materials Laboratory at ITU. His research interests include durability, service life and permeability of concrete and structures, cementitious binders, chemical admixtures, fiber reinforced composites, quality control of concrete and testing of concrete.

Riadh Al-Mahaidi

Dr. Riadh Al-Mahaidi is a professor of Structural Engineering and Director of the Smart Structures Laboratory at Swinburne University of Technology in Melbourne, Australia. Over the past 20 years, he focused his research and practice on the lifetime integrity of bridges, particularly in structural strength assessment and retrofitting using advanced composite materials. He received a B.Sc. (Hon 1) degree in civil engineering from the University of Baghdad and M.Sc. and Ph.D. degree in structural engineering from Cornell University in the USA. To date, he published over 250 journals and 270 conference papers. He is a fellow of the Institution of Engineers Australia, American Society of Civil Engineers, Institution of Civil Engineers (UK), American Concrete Institute, International Institute for FRP in Construction, and the Bridge Engineering Institute.

Ashraf Ashour

Ashraf Ashour is a professor of Structural Engineering at the University of Bradford, received his Ph.D. from Cambridge University, was the head of Civil Engineering Department between 2007–2012, and the director of Research at the School of Engineering between 2014–2018. He is the director of the Bradford Centre for Sustainable Environments (BCSE) at the University of Bradford. He is a fellow of the Institution of Structural Engineers (FIStructE) and a senior fellow of the Higher Education Academy (SFHEA). He has extensive research experience in the development of new sustainable construction materials and their use in sustainable infrastructure as well as techniques to extend the life of concrete structures. He has published more than 250 journal and conference papers. He was the editor-in-chief of the Structures and Buildings Journal (ICE) and is currently an associated editor of Structures, Elsevier. He was recently awarded Newton Prize – 2020.

Altok Kursun

Altok Kurşun received his M.Sc. in Civil Engineering-İTÜ in 1967. His experiences are: Between 1968–1972, Bridges Project Engineer in the first Bosphorus Bridge and Ring Roads Project at the 17th Regional Directorate of Highways; between 1972–1985, design and control engineer on viaducts and bridges in Germany; between 1985–1991, chief design engineer in the Kınalı-Sakarya Highway and Fatih Sultan Mehmet Bridge Project; between 1991–2000, general manager of Engineering Company, general manager of Engineering Group Companies, and chairman of the Board of Subsidiaries in STFA Group; between 2001–2004, a freelance consultant; between 2004–2011, rail systems coordinator and member of the Executive Board of Partnerships at Doğuş İnşaat A.Ş; between 2012–, member of the Executive Board and technical coordinator at Gülsan Group of Companies. Simultaneously, as a Guest Lecturer Bridge courses at İTÜ Faculty of Civil Engineering.

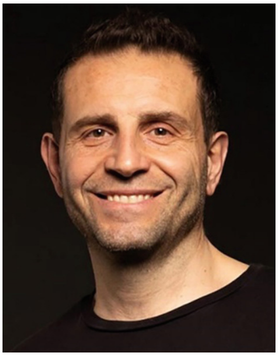
Bing Li

Dr. Li received his Ph.D. from the University of Canterbury, New Zealand. He has over 25 years of experience in design, research, and educational aspects related to structural concrete and has led many research projects involved with the modeling, design, analysis, and full-scale structural testing of reinforced concrete and precast concrete building systems. His publications include more than 160 research papers in leading structural journals. His fundamental contributions are in the fields of seismic, blast-resistant design of reinforced concrete structures.

Marco Di Ludovico

Marco Di Ludovico is an associate professor at the Department of Structures for Engineering and Architecture, University of Naples Federico II. He is the author of more than 250 scientific papers published in journals or proceedings of national and international conferences. His research activities focus on theoretical and experimental work in the field of strengthening of PC girders, RC, and masonry structures with composite materials (FRP, FRC, FRCM, CRM, and FRM); post-earthquake damage and performance loss, fragility curves, expected losses, reparability of existing structures; structural health monitoring; innovative technologies for restoration and protection of Cultural Heritage. He is a member of fib bulletin TG 9.3 “FRP Reinforcement,” TG 5.1, CNR-DT 200, CNR-DT 215/2018, technical committee for developing Commentary to Italian Building Code NTC 2018, European Association for Earthquake Engineering (EAEE), Working Group 1 (EC8) Future Directions for Eurocode 8. He is a co-founder of the spin-off SEISMART srl, Sustainable Engineering, Innovative Solutions & Materials for Anti-seismic Reliable Techniques.

Emre Ortemiz
He was born in Mersin in 1986. After completing his primary, secondary, and high school education in Mersin, he graduated from Istanbul Technical University Civil Engineering Department in 2013. In 2020, he graduated from Galatasaray University Business Administration Master's Program. After working in various construction projects between 2011–2015, he worked as Ready-Mixed Concrete Plant Supervisor at Oyak Beton between 2015–2018. Emre ÖRTEMİZ, who worked as a quality executive in the Ready-Mixed Concrete Technical and Quality Department of Akçansa A.Ş. in 2018 and 2019, has been working as the Quality and R&D Manager at İSTON A.Ş.



Alessandro Palermo
Prof. Palermo is a professor in structural engineering at the University of Canterbury, New Zealand. He is a renowned researcher in the field of seismic low-damage technologies, and he has been exposed to several New Zealand post-earthquake reconnaissance missions in the last decade. His recent research also expands to material aging, use of durable materials (glass reinforcing and ultra-high-performance concrete) and recycled materials (rubberised concrete), tessellated materials (auxetic), and digital fabrication (3D concrete printing). Alessandro is an author of more than 370 international conference and journal papers and 3 patents. In 2020, he was one of the top 2% most cited researchers in SCOPUS. He has been awarded several national and international awards including the 2020 ASCE Alfred Noble Prize for a co-authored technical paper, the 2021 IABSE best technical paper and more recently the 2021 "Most Influential International Accelerated Bridge Construction Person of the Year Outside U.S." in Academia.

He is currently fib New Zealand Head Delegate and President of Concrete NZ Learned Society which counts over 400 members. He is also the chair of the IABSE NZ group which was recently awarded the inaugural best 2022 National Group of the Year. Prof. Palermo is also a very passionate teacher. He received several teaching awards. He received 5 awards from the University of Canterbury Student Association, being voted by the students Best Lecturer of the Year at the University of Canterbury (more than 850 academic staff). In 2019, he was the recipient of the University of Canterbury Teaching Award, and in 2021, he was one of three finalists at the Engineering NZ awards (ENVI) education category.

Murat Saatcioglu

Dr. Murat Saatcioglu is a distinguished university professor in the Department of Civil Engineering of the University of Ottawa, Ottawa, Canada. He received his B.S. in Civil Engineering from the Middle East Technical University, Ankara Turkey, his M.A.Sc. in Structural Engineering from the University of Toronto, Toronto, Canada, and his Ph.D. in Structural Engineering from Northwestern University, Evanston, Ill., USA. He is a fellow of the Canadian Academy of Engineers, Engineering Institute of Canada, American Concrete Institute (ACI), and the Canadian Society for Civil Engineering (CSCE). Dr. Saatcioglu's research interests include analysis, design, and retrofit of structures subjected to extreme loads, including those caused by earthquakes and bomb blasts. He has conducted extensive experimental and analytical research on earthquake and blast-resistant structures and contributed toward the development of codes and standards, nationally and internationally.

Professor Saatcioglu is the recipient of numerous national and international research and teaching awards and medals, including the 2015 A.B. Sanderson Award of CSCE for outstanding contributions to the development and practice of structural engineering in Canada; the 2014 Whitman Wright Award of CSCE for significant contributions to the advancement of innovation and information technology in civil engineering; the 2001, 2004, and 2015 Casimir Gzowski Medals for best papers in the Canadian Journal of Civil Engineering; the 2004 Wason Medal of ACI, the 2000 Raymond C. Reese Research Prize of the American Society of Civil Engineers for outstanding contributions to the application of structural engineering research, the 2005 CCEDS-1 Award for Best Paper from McMaster University; and the 1989 Charles Whitney Medal of ACI. In 2021, he was listed among the World's Top 2% Scientists in all categories by Stanford University.

Larbi Sennour

Dr. Larbi Sennour is the president of CEG-International, a precast concrete specialty engineering firm. He has a bachelor from Ecole Polytechnique in Algiers, Masters, and Ph.D. from the University of Texas at Austin. He is the past PCI Technical Activities Council chair and a member of the PCI R&D Council. He is also a member of ACI committees 314, 533, 319 (Precast Code) and past chairman of ACI 550 (Precast Concrete Structures). He is also involved internationally. He is a member of fib presidium and co-chair of fib commission 6 (prefabrication). Dr. Sennour has several publications in both materials and structures. He was the vice chair of the Industry Handbook Committee 8th edition of the design handbook. Dr. Sennour is licensed to practice engineering in 30 states.

Thanasis Triantafillou

Thanasis Triantafillou is a professor and head in the Department of Civil Engineering at the University of Patras, where he has been working since 1993. He received his M.Sc. (1987) and Ph.D. (1999) degrees from MIT, where he served as an assistant professor from 1990–1993. He holds the title of Visiting Global Distinguished Professor at New York University Abu Dhabi. His main research interests are focused on the application of advanced materials in structures, with emphasis in the field of seismic and integrated seismic/energy retrofitting of concrete and masonry. He has limited research activity in steel-concrete composite construction, structural health monitoring, alkali-activated materials, and fire engineering. Prof. Triantafillou is the recipient of three Medals, and three Best Paper awards (from ASCE Journals). He is a member of International and National Scientific Committees and Societies, an associate editor for two International Journals (ASCE J. of Composites for Construction, J. of Composites Science) and member in a number of International Journal Editorial Boards.

Agnieszka Bigaj-van Vliet

Dr.ir. Agnieszka Bigaj-van Vliet is a senior expert in the field of safety and durability of concrete structures. She holds an M.Sc. degree in civil engineering from Warsaw University of Technology and a Ph.D. in civil engineering from Delft University of Technology and has worked at the Netherlands Organization for Applied Scientific Research (TNO) for over 20 years. Agnieszka is involved in high-end consultancy projects of TNO and coordinates several research programs, including research on smart and sustainable concrete structures with circular solutions, and research on data-informed assessment supported by Structural Health Monitoring. Agnieszka is a Presidium member of the International Federation for Structural Concrete (fib), a member of the fib Technical Council, and head of the Dutch national delegation to fib. She is deputy convener of the fib TG10.1 Model Code for Structural Concrete. She is also a member of subcommittee 318-L, International Liaison, of ACI Committee 318-25, Structural Concrete Building Code.

Elizabeth Vintzileou

Elizabeth Vintzileou is a professor of Reinforced Concrete and Masonry Structures at the School of Civil Engineering, National Technical University of Athens, Greece.

Her research focuses on the behavior of new and existing RC and masonry constructions, repair/strengthening techniques, reinforced concrete interfaces, documentation and rehabilitation of monuments (buildings, bridges, ancient monuments), etc., with emphasis on structures subjected to cyclic actions. She has coordinated over fifty (national and international) research projects. She has authored/co-authored more than three hundred publications in Journals, Conference Proceedings, Books.

She is member of the two Central Councils (Central Archaeological Council and the Central Council for Modern and Contemporary Monuments) of the Hellenic Ministry of Culture.

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Contents

25 Years Working with Green Steel Slag Concrete

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Abstract. Industrial production of iron and steel within Spain has historically been situated in the north area of Spain. Although a major economic activity for the region, the industry also generates large volumes of waste that have hitherto been dumped in unsightly landfill sites. Over 25 years ago, a group of engineers and researchers from the same area set themselves the challenge of regenerating this waste. In this study, the advances developed in the technology of green slag concrete are reviewed, focusing on the expertise that the research group has accumulated over the past 25 years. Electric arc furnace slag is a stony material that is now often used as aggregate in hydraulic and bituminous mixes. Its use in hydraulic cement-based materials and the important properties of slag aggregates for mix workability are analyzed. Likewise, the mechanical behavior and the durability of slag concrete specimens is presented, paying special attention to expansive compounds and to the performance of electric arc furnace concrete in marine environments. In addition, real scale elements manufactured with slag concrete and their behavior are analyzed, as well as the advantages of applying current standards to their design. Finally, new lines of research are discussed for the use of electric arc furnace slag in cement-based materials.

Keywords: Electric arc furnace slag · green concrete · mechanical behavior · concrete durability · reinforced concrete

1 Introduction

The Basque Country has been at the core of the steel industry for centuries. Its iron mines and forests made this region one of the largest steel producers at a European level [1]. Over 40% of all steel production in Spain has taken place within this region [2]. Although steel production has been falling, it is still of some importance within a region of a 7234 km^2. While positive for the regional economy, the generation and management of iron and steelmaking slag has been a contentious environmental issue.

Since 1996 when "Altos Hornos de Vizcaya" closed down, the Electric Arc Furnace (EAF) has been the preferred technology for steel produced in the Basque Country. The

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main waste streams are Electric arc furnace (EAF) slag and subsequently, Ladle furnace (LF) slag. In harmony with European directives [3, 4], the Basque Country has adopted policies to reduce, reuse and recycle waste over the past decade [5, 6].

Following this trend, a group of researchers located in the north of Spain (University of Burgos, University of Cantabria, University of Basque Country, Tecnalia Research center, and Gikesa) started to work with the main objective of looking for the way to reuse EAF and LF slag.

Geiseler, Motz and Koros were the first researchers who perceived the opportunity for the reuse of steel slag within the construction sector [7–9]. Following their example, this group of researchers began to study the reuse of EAF and LF slag and its incorporation in cement, concrete, and bituminous mixes. The research group published its first works in the late 90s and the first years of the 2000 [10–12], after which several works were developed with the same objective: the use of EAF slag and LF slag in cement-based materials [13–15] and bituminous mixes [16, 17]. The soil stabilization properties of LF slag have also been studied [18].

Following the innovative proposals of the abovementioned pioneers, the work of this research group has been focused on the “massive” use of EAF slag and LF slag in construction applications, and sharing the knowledge learnt over the 25 years of working with these aggregate materials. The use of the term “massive” implies an eventual large-scale utilization. Since the start of research within this area, our work has built on the initial approach of the pioneers: both EAF and LF slag are excellent aggregate materials in themselves, which when complemented with other “more conventional” materials, can enhance and optimize performance.

2 EAF Slag

EAF slag is a hard stony by-product of steel refining processes. The molten slag at 1560 °C is poured from the tilting furnace on the deslagging side and then cooled, either after continuously dousing the slag with water or after pouring the slag into a large pit and then sprinkling cold water onto its surface. It has been observed that the cooling method can affect slag porosity. When cold dousing the slag, its porosity is higher as it cools, due to the entrapment of gases within the hot slag that could not escape; on the contrary, the slag cooled after sprinkling the surface is less porous and thicker. The cooling rate also affects the resultant gradation of the slag particles. With fast cooling, particles smaller than 40 mm are formed and with slower cooling, the particles are larger than 40 mm. Nevertheless, in both cases a crushing process is needed to obtain different grades. The gradation of gravel sizes is good and the distributions that are normally obtained are similar to natural aggregates. In the gradation of sand sizes, the content of fines is generally, very limited, and it is difficult to find an EAF fine slag with 20% or more particles smaller than 1 mm.

EAF slag normally has a higher density than natural aggregates: the different values recorded are between 3–4 t/m^3. The main parameters that affect the density of EAF slag are the content of metallic iron and iron-manganese oxides and the porosity of the slag.

The chemical composition of the slag depends on the raw materials and processes used to manufacture the steel. In Table 1, the typical chemical compounds found in

EAF slag are shown alongside their proportions. It may be observed that the ratio of the different compounds can significantly vary, but the main compounds are iron, calcium and silicon oxides.

Table 1. Chemical composition

Compounds (%)	Top
Fe_2O_3	15–40
CaO	26–43
SiO_2	8–20
Al_2O_3	3,5–12
MgO	3–6.5
MnO	3–5
SO_3	0.01–0.4
P_2O_5	0.4–0.6
TiO_2	0.5–0.8
$Na_2O + K_2O$	0.1–0.2

It is possible to find free lime in EAF slag, generally in proportions smaller than 5%. It could be the main problem for the use of EAF slag as aggregate in cement-based material, due to its expansiveness. However, it has been demonstrated in the literature that the initial expansivity of the slag can be reduced to acceptable values, after crushing and magnetic separation of metallic fragments, if it is periodically turned and sprinkled with water while left to weather for 90 days [19].

3 Mix Preparation

Insufficient attention may have been paid to aspects of mix design in the first experimental campaigns developed to evaluate the behavior of EAF slag [20]. The usual proportions and procedures for natural aggregates were used. Nowadays, there is far greater knowledge of mix design in EAF slag concrete [21, 22] and there are three aspects that should be highlighted.

As has been mentioned above, EAF slag normally has insufficient fine aggregate fractions smaller than 1 mm; so if EAF slag is used as sand replacement, 100% of the natural aggregates cannot be replaced, it being necessary to complement the finer fraction with 0–1 mm sized natural aggregates. In addition, it has been demonstrated that the role of the fine fraction is even more important in EAF slag concrete than in natural aggregate concrete. So, the addition of this fine natural aggregate is mandatory to obtain good concrete.

Second, not all the superplasticizer/plasticizer admixtures work suitably in the presence of EAF slag. Although it is supposed that the superplasticizers/plasticizer admixtures react only with the cement, there is interaction between some of them and the EAF slag. It has been seen that the effect of this admixture is sometimes decreased or even annulled when EAF slag is used. So, before starting any experimental campaign, it is recommended that interaction between the superplasticizer/plasticizers and EAF slag be tested.

Finally, it is important to consider slag water absorption levels when the mix design is prepared. If the slag is used with storage humidity it is important to measure it and add more water to the mix if too dry. Humidity must be measured every time a mix is prepared, to avoid possible humidity changes in the place of storage. Also, good results are obtained, if the EAF slag is doused with water the day before its incorporation in a concrete mix.

4 Fresh Properties

The consistency of the concretes manufactured with EAF slag has commonly been a problem for its use. It is more difficult for cement paste to transport EAF aggregate particles than to transport natural aggregates, due both to their higher superficial roughness and density. Therefore, the consistency of mortars and concretes manufactured with EAF slag is, in general, worse than the consistency of mortars or concretes manufactured with natural aggregates.

However, after several years of research, it was observed that concrete and mortar could be manufactured with the desired consistency when the mix design was carefully calculated. If the aspects mentioned in the previous section are considered, it is even possible to manufacture self-compacting concrete using EAF slag as aggregate [21], as can be seen in Fig. 1. The most important aspect is the addition of natural fine fractions. In this case, it is necessary to design a cement paste with increased viscosity to transport the aggregates, which can be done by increasing the fine fraction of the concrete. Hence, the greater importance of the fine fraction in EAF slag concrete, as mentioned in the previous section, than in ordinary concrete manufactured with natural aggregates.

Fig. 1. Self-compacting concrete manufactured with EAF slag concrete

5 Hardened Properties

In general, all the studies developed in the last 25 years have shown that the hardened properties of concretes manufactured with EAF slag are similar to the properties of concretes manufactured with natural aggregates [20, 21, 23–25].

The density of EAF slag concretes is higher than the density of natural aggregates concretes, as may be expected considering the density of both aggregates (3–4 t/m^3 for EAF slag and around 2.7 t/m^3 for natural aggregates). In all the elements that work by gravity this is advantageous, but in structural concrete the higher density of the concrete can be a weakness. For this reason, some attempts to decrease the density of EAF slag cement mixes have involved air entrainment admixtures. However, it was observed that this admixture decreased the strength of the mixes, and the decreased density hardly compensated the decreased strength [22, 26]. The conclusion was that the option of heavier concretes without air entrainment admixtures was the preferable option.

The mechanical behavior of concretes manufactured with EAF slag is normally similar to the behavior of natural aggregate concrete and when a good mix design is used even better mechanical properties have been found in EAF slag concretes than in natural aggregates concrete.

In the literature it has been concluded that the main reason for obtaining higher strengths using EAF slag is the denser ITZ that is generated between the EAF slag and cement paste than natural aggregate and cement paste [14, 27]. The properties of the slag mean it has better adhesion with the cement paste. In addition, it has been demonstrated that there is a migration of free lime from the core to the periphery of the aggregate sizes in stockpiled EAF slags. A transition that contributes to a denser Interfacial Transition Zone (ITZ) when the calcium oxide or free lime, CaO, that migrates to the aggregate surface reacts with water and is converted into calcium carbonate, $CaCO_3$. In Fig. 2, the differences between the ITZ of a natural and an EAF slag aggregate concretes may be seen.

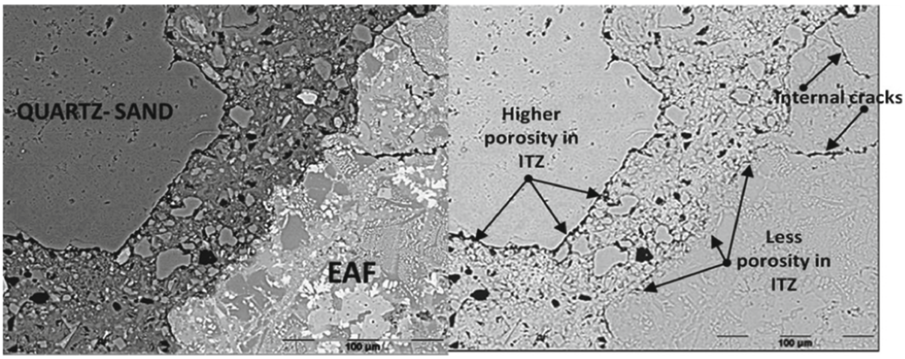

Fig. 2. Microstructure of EAF slag concrete [14]

Furthermore, it is understood that the morphology of the ITZ also plays an important role in the permeability and, therefore in the durability of the mixes. The durability of EAF slag concretes has been studied in many experimental campaigns [19, 28–30]. Different accelerated ageing tests have been developed to study it, among which the autoclave test and the study of the behavior of EAF concrete in marine environments are worth mentioning.

The autoclave test has been used to study the dimensional stability of the mixes, the specimens were placed in an autoclave at 130 °C and 0.2 MPa [21, 22]. The main objective was to accelerate the hydration/carbonation of the free lime and free magnesia. In Fig. 3a, a sample may be seen before performing the autoclave test. In Fig. 3b, a mix with only EAF slag as aggregate is shown, which maintains its volumetric stability after having performed the test. If the mixes have expansive compounds which can damage the specimens, the appearance of the sample after performing the test is similar to Fig. 3c.

Fig. 3. a. (Sample A5 before testing); b (Sample A3 after testing); c (Sample A5 after testing).

It has therefore been demonstrated that if the EAF slag aggregate is used after a suitable weathering period, no problems of dimensional stability will be found.

The importance of the study of the behavior of the EAF slag concrete in marine environment, is because the Port Authority of Bilbao has encouraged the use of this material for building sea walls to protect the docks and the foundation of the Puntasollana dock [31]. In tests for that purpose, various specimens were placed in a cage suspended from a sea wall in the port of Pasaia in an inter-tidal zone (Fig. 4). When the tide comes in, the specimens were submerged under the water and when the tide went out, the cage and its contents were exposed to the air. The specimens were broken into two halves and the chlorine and sulfate ion concentrations were measured. The results were in all cases similar to natural aggregate concretes [28].

6 In-Service Behavior

In the territory of the Basque Country there are several practical examples of real hydraulic and bituminous engineering projects and soils stabilizations (buildings, docks, pavements…), which include large amounts of slags [32]. Although they each deserve their own description, the durability analysis and the mechanical behavior of structural elements, derived from previous tests, are indispensable to verify the utility of these sorts of bound mixtures.

Fig. 4. Cages suspended in an inter-tidal zone at the port of Pasaia

Several works on the study of the durability of these mixtures after the standard tests, such as freezing-thawing, wetting-drying, sulfate attack… and other more innovative tests such as accelerated aging under temperature, carbonation of concrete, pH evolution, reinforcement protection… have been performed and this research group has published the results in various papers [30]. The results have advanced notably in terms of durability enhancement from the initial studies of [19] to more recent ones [28, 29]; as mix designs and the global know-how increased, so too did mix durability.

After learning how to manufacture high quality concretes with EAF slag as aggregate, the goal was to manufacture real scale elements and study the suitability of reinforced EAF slag concrete components *in situ*. In recent years, one focus of this research group has been to analyze the structural behavior of EAF slag reinforced concretes.

Several 4 and 5.4 m beams with cross sections of 200 mm × 300 mm were manufactured for testing. The beams were submitted to bending tests [33], shear strength tests [34], and long-term deflection under sustained loading tests [35]. In-depth analyses of different test results may be found in the literature, but a brief conclusion is that in general the structural behavior of EAF slag reinforced concrete beams is good and the presence of EAF slag is a favorable factor in the assessment. An especially excellent result was the behavior withstanding delayed deflections in service under sustained loading of usual intensity.

It has also been shown that the current structural code can be used in the design process of these reinforced concrete components. The final result showed that these concrete mixtures are ready to be used in any structural components. A subsequent research objective is to pour and to test post-stressed type beam and slab elements. The research group are confident that good results may be obtained.

7 Conclusions

After 25 years working with EAF slag (and LF slag) as aggregate in cement-based material mixes, the utility of this waste stream and its suitability for use in such applications is beyond doubt. If the measures presented in this paper are followed, high quality concrete mixtures can be produced. The performance of each mix is not so very different from natural aggregate concretes, and it has been shown that existing codes can be use when reinforced concrete is manufactured with EAF slag aggregates.

This group of researchers is convinced of the utility of this material and is researching new applications, which not only replace the natural raw materials, but also obtain added value from their use. The idea is to study its electrical conductivity, thermal conductivity, and magnetic properties, and to look for new applications in which the characteristics of the EAF slag could be advantageous.

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