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THE INDIAN CONCRETE JOURNAL

Published by ACC Limited

Volume 95 • Number 5 • May 2021 • Pages 64 • ₹ 175

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Volume 95 • Number 5 • May 2021 • Pages 64

ISSN (Digital) : 0019-4565

Founded in 1927

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Cover

The knowledge and the lessons learned from the construction of the 2012 London Aquatics Centre, helps raise the bar within construction industry, and is a legacy showcase project for usage of secondary aggregates in visual concrete with high quality finish.

Cover image source:

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Contributed by:
Sara Klomps, Director at
Zaha Hadid Architects

CIRCULATION OFFICE: The Indian Concrete Journal, ACC Limited. L.B. Shastri Road, Near Teen Haath Naka, Next to Eternity Mall, Thane (West) 400 604, Maharashtra, INDIA.
Website: http://www.icjonline.com; e-mail: info@icjonline.com, editor@icjonline.com

Dear Readers,

We are pleased to bring to you our tetralogy edition on Construction & Demolition (C&D) waste in Construction. This edition includes research and practice papers providing a comprehensive view of recent developments on this theme across geographies and the possibilities it holds. This edition has been guest edited by Dr. Sivakumar Kandasami and Prof. Dr.-Ing. Jiabin Li.

Dr. Sivakumar Kandasami is a trained concrete technologist with the Construction Division - Buildings & Factories IC of Larsen & Toubro (L&T). His Ph.D. work at the University of Dundee (UK) was on concrete durability and his expertise is frequently sought for mega projects designed to last an intended service life. He takes keen interest in developing robust solutions for concreting challenges at site, involves in R&D efforts within L&T, regularly reviews manuscripts for scholarly journals and is on the Technical Board of the Indian Concrete Institute (ICI). The Institution of Civil Engineers (ICE), UK awarded him the MCR PRIZE 2012 for the best paper published in the *Magazine of Concrete Research*. He is an Editorial Board Member of *Construction Materials* (ICE, UK) and *Journal of Testing and Evaluation* (ASTM, USA). He is a Fellow of the Institute of Concrete Technology (ICT), UK and the Institution of Engineers (India). Dr. Kandasami represents India in the Council of ICT and L&T in the General Council of ICI.

Prof. Dr.-Ing. Jiabin Li is a Professor of Civil Engineering with a research focus on recycling and reuse in construction at KU Leuven, Belgium. He received his Master degree in Structural Engineering in 2004 from Tongji University with an award-winning thesis on the behaviour of concrete with recycled concrete aggregates. In 2011 he obtained his Ph.D. in Civil Engineering from Leipzig University. He joined KU Leuven in 2016 and has been the head of the research group RecyCon since October 2018 and the coordinator of Research and Education Civil Engineering on Bruges Campus since August 2020. He is the holder of three industrially sponsored research Chairs at KU Leuven in smart & sustainable infrastructure, construction waste recycling and circular construction economy, respectively. Prof. Dr.-Ing. Li was a recipient of the SEMC 2010 Young Researcher Fellowship Award.

Production Editor
Indian Concrete Journal

Dear Colleagues,

Firstly, we would like to greet all readers of the Indian Concrete Journal (ICJ) and we sincerely wish you to stay safe and healthy during the COVID-19 pandemic. Welcome to the fourth special edition of ICJ on Construction & Demolition (C&D) Waste in Construction, which is composed of invited papers by authors from India, UK, South Africa, and Belgium. Such an international spread of contributions shows the constant reinvention happening continually across the world to tackle the huge amount of C&D waste and the consequent searching for new possibilities in the valorisation of C&D waste after processing.

We sincerely thank all the authors for their kind acceptance of the invitation and hopefully this special edition can promote new research and practical implementation of building materials and products with recycled C&D waste. We are excited to introduce the contents of this issue which can hopefully drive genuine conversation between stakeholders.

The leader article by Klomps (2021) introduces the successful utilisation of sustainable concrete in the Aquatics Centre of the 2012 London Olympics to meet the sustainability objectives set by the Olympic Delivery Authority. Meeting the set sustainability targets was found to be a big challenge during the design and construction both in terms of cement replacement as well as the incorporation of recycled aggregate. The paper explains in detail how the predefined sustainability targets were reached by adopting various strategies, which included the incorporation of recycled aggregates and recycled water, the substitution of cement with supplementary cementitious materials (SCM), sustainable transport of materials and so on, leading to maximising the sustainability of the concrete by achieving over 4,000 tonnes of embodied CO_2 savings and substitution of over 29,000 tonnes of primary aggregate.

The paper by Amadi, Alexander and Beushausen (2021) provides a critical review of sustainability of aggregates for cement-based materials. In their paper, the growing demand for natural aggregates in concrete, especially sand and coarse aggregate, and their global environmental and socio-economic effects are highlighted. Different factors driving future aggregate demand, such as transport and power infrastructure, land reclamation, and housing projects are examined. The paper also gives a very good examination of the effect of the urbanisation, population growth, and economic growth on aggregate consumption in different regions of the world. Finally, it is concluded that the use of recycled aggregates, crushed sand, and slag aggregates are important sustainable alternatives to natural sand and coarse aggregates for concrete in the future.

Recycled concrete aggregates (RCA) derived from crushing old concrete have been proven to be a viable material for producing structural concrete and even high strength high performance concrete (e.g. Xiao *et al*. 2005; Xiao *et al*. 2006; Sierens and Li, 2018). Can this material be used to produce even higher-grade materials? The paper of Sierens, Joseph and Li (2021) provides a feasibility study on using coarse RCA to produce ultra high performance concrete (UHPC). The laboratory test results indicate that it is possible to manufacture UHPC with RCA through a proper selection of the constituents and mix design. The developed UHPC with RCA achieved record high compressive strengths, up to 160 MPa. This research work significantly explored the use of RCA further up the value chain.

The paper by Biswal and Dinakar (2021) presents an interesting study on the use of coarse RCA to fully substitute coarse natural aggregates in developing self-compacting concrete (SCC). The all-in aggregate grading curves in the DIN standard were employed. To further improve sustainability of the SCC mix, different SCMs were also used. Both the fresh properties and the compressive strength of the developed SCC mixes at different curing ages were measured. The test results indicate that the DIN all-in aggregate grading provides better workability and mechanical properties in comparison to BIS all-in aggregate grading method, especially when SCMs are included.

A second research dealing with SCC mixes using recycled materials in this special issue is provided in the paper of Ajay, Joshi, Girish and Bharadwaj (2021). The authors reported a comprehensive laboratory work on manufacturing M30 grade SCC using IS: 10262. A total of five different SCC mixes were produced by utilizing fly-ash and Ground Granulated Blast Slag (GGBS) as filler materials along with natural river sand, marble dust, fly-ash, dried ready-mix concrete sludge, and granite sludge as fine materials. The used coarse aggregate has a maximum size of 20 mm. The fresh properties, microstructure and compressive strength of the developed SCC mixes were investigated. The test results reveal that the developed SCC mixes exhibited satisfactory performance. In addition, the SCC mixes with fine materials such as granite sludge showed better performance compared to other fines.

Many previous studies have shown the utilisation of recycled aggregates (RA) from C&D waste in producing both non-structural and structural materials and products is technically feasible and economically viable. However, whether the use of RA can really lead to environmental benefits and improve sustainability is still frequently questioned due to its inherent complexity. This closing paper of this special issue, contributed by Thomas, Sankaran, Jisha and Dhanya (2021), provides an attempt to assess the sustainability of M25 grade concrete incorporating coarse RA at different replacement percentages to natural aggregates, following a cradle-to-gate life cycle assessment approach. In their work, the mix design parameters of the concrete were suitably modified with the increase in replacement percentages of RA at achieve the strength requirement. The assessment of the environment impact was carried out by means of the CML 2001 baseline method. The authors have pointed out that the environmental burden with concrete could be reduced in case of an optimum usage of coarse RA.

As Guest Editors sitting in different parts of the world, we could virtually meet and co-ordinate with the Production Editor to bring out this special issue amidst the raging pandemic. Once again, we thank all the contributors and the reviewers for their equally valuable support in enhancing quality of the papers.

We would like to recommend reading all the papers to our readers and believe that the content is very useful, not only for further research but also for practice.

Enjoy your reading!

Regards,

Sivakumar Kandasami
Jiabin Li
Guest Editors for the Special Issue, ICJ

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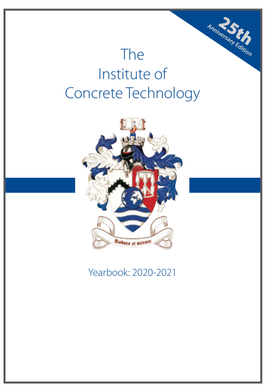
BOOK REVIEW



The latest edition of the ICT Yearbook is now out – a 'silver' edition to celebrate 25 years of publication. And it is bumper edition, with new features and additional content. A foreword by Prof. Peter Hewlett, the long-standing chairman of the editorial panel, reviews the Yearbook's growth over the period since 1996, and two articles introduce the ICT's most recent developments: the Institute's webinar programme and the new partnership with RILEM. The core content consists of eight technical papers presented at the annual ICT Convention, commencing with a keynote paper by Prof. Phil Purnell, 'Between a rock and a hard place', but is extended by several commissioned papers from members of the Institute. These papers address such subjects as superabsorbent polymers, the water ponding curing method and carbon neutrality for concrete. A short piece on site acceptance of concrete entitled 'What not to do' distils members' experience of poor practice, to illustrate the value of training and qualification. Regular features are retained, with Prof. Rod Jones the subject of this year's 'face-to-face' interview, and John Lay describing the work of the Examinations Committee. Historical topics are treated with Wilhelm Michaelis (1840-1911) this year's 'Pioneer of concrete technology' and the GPO Building this year's 'Significant concrete structure'. A guest piece by the World Cement Association's chief executive considers 'The global cement industry and technology: past present and future'. As usual the Yearbook concludes with abstracts of the latest dissertations and project reports to have been awarded the Diploma or MSc in Advanced Concrete Technology. Copies are available for purchase from ict@concrete.org.uk

RILEM UPDATE

The International Union of Laboratories and Experts in Construction Materials, Systems and Structures

RILEM YouTube Channel

In 2014 RILEM set a challenge for itself by launching its own YouTube channel. For the last 7 years, this platform has educated and informed thousands of viewers through **FREE videos** of the lectures of the Gustavo Colonnetti and Robert L'Hermite medallists, the recording of the ROC&TOK monthly webinars and the presentations of RILEM Technical Committees and experts! This channel also features some promotional videos of the association via different testimonies of researchers/persons playing an essential role within RILEM. You have just to click now and enjoy: youtube.rilem.net!

75th RILEM ANNUAL WEEK

The keynote and plenary speakers at the **75th RILEM Annual Week** and *International Conference on Advances in Sustainable Construction Materials and Structures,* in September 2021 in Merida - Mexico, have been recently announced! Check for details of these experts at rilemweek2021.uanl.mx/confirmed-speakers. Do not miss the opportunity to listen to their talks. Registration for the event is now open! The program consists of eight segments bringing together latest developments to improve the quality assurance in construction materials and testing, together with doctoral courses, seeking to attract participation of young researchers and professionals from the construction industry.

GLOBE

RILEM is proud to give its support to the **GLOBE** initiative - the Global Consensus on Sustainability in the Built Environment - whose main objective is to direct the attention of the global community, politicians, industry leaders and societal decision-makers to the critical importance of the built environment for sustainable development at global and local scales. Please, consider to give your support through this page: globe.rilem.net! Since its establishment in 2020, 18 Organizations and 99 Individuals have given their supports.

THE USE OF SUSTAINABLE CONCRETE IN THE LONDON AQUATICS CENTRE

SARA KLOMPS

1. EMBODIED ENERGY IN CONCRETE – SOME FIGURES

- Concrete is the most common construction material used worldwide. The average embodied energy for concrete is around 2 MJ/kg, with the range being 0.86 MJ/kg to 5.4 MJ/kg.
- Cement is up to 4.5 times more energy intensive to produce than concrete as a whole and is responsible for approximately 5% of the worldwide CO_2 emissions, as well as emissions of NOx and SO_2 and millions of tons of the waste product cement kiln dust each year contributing to respiratory and pollution health risks.
- CO_2 emissions are both raw material-related (60% of all emissions) and energy-related. Raw material-related emissions are the result of limestone decarbonation during the calcination process; energy-related emissions are generated both directly through fuel combustion and indirectly through the use of electrical power.
- Energy consumption in the cement industry has declined significantly over the past 50 years, mainly due to technological improvements. Each ton of cement produced requires 60-130 kg of fuel oil or an equivalent fuel and about 110 kWh of electricity.
- The fuel combusted for the burning of raw materials represents approximately 80% of the overall energy consumed in the production of cement. The remaining 20% is in the form of electrical energy used for grinding and kiln exhaust fans.
- Reducing the amount of cement by incorporating secondary materials or by-products of other industries, such as granulated blast furnace slag (GGBS) and pulverized fuel ash (PFA), by-products of iron manufacture and energy generation from coal respectively, allows for a CO_2 reduction.
- Crushed concrete can be used as aggregate in the manufacture of concrete increasing its recycled content and thus its embodied CO_2.

2. SUPPLEMENTARY CEMENTITIOUS MATERIALS

- Blast furnace slag is a by-product of the iron industry. The global availability of blast furnace slag is relatively low and decreasing, therefore it cannot replace the massively demanded clinker in some regions.
- Fly ash results from the combustion in coal power plants. Its availability is greater than slag's but due to a huge variation in quality only one-third of the produced quantity is used in the cement and concrete industry.
- Silica fume (micro silica) is a by-product of silicon metal in electric arc furnaces.

Due to its finer size it is helpful in making a denser microstructure of concrete. Unfortunately, silica fume is an expensive product that is mainly used in high strength concretes, and with a limited production rate, it cannot be used for clinker substitution.

- Calcined clays, particularly in combination with lime stone, are found to be the extremely promising materials that are available in large enough amounts and have real potential to replace part of the clinker in cement production. Clays are abundant materials worldwide and made up of silicon and aluminum oxides, which constitutes three quarters of the earth's crust.

3. SUSTAINABLE CONCRETE FOR THE LONDON AQUATICS CENTRE 2012

London's bid for the 2012 Olympic & Paralympic games was based on a redevelopment plan for the the Lower Lea Valley, a 200-hectare rehabilitation and regeneration project in the poorer East London for which the games would act as a catalyst. Equally important was to achieve this in a sustainable manner leaving a long lasting legacy for London.

Following London's successful bid in 2005, the Olympic Delivery Authority (ODA) was established, whose central job was to deliver venues, facilities and infrastructure and transport in a way that 'maximised the delivery of sustainable objectives, on time and within the available budget' [Olympic Delivery Authority - sustainable development strategy, 2006].

In order to set out the key policy priorities to reach these goals, the Olympic Board published the London 2012 Sustainability Policy in 2008. For the procurement of materials for the Olympic Park, the ODA aimed to identify, source and use environmentally responsible materials.

In terms of volume, concrete was identified as the second most widely used material in the Olympic Park after engineered fills. Initial estimates made for the Olympic Park indicated that 500,000 m^3 of ready-mix concrete would be required to build the sporting venues and supporting infrastructure with an equivalent aggregate requirement of approximately 1.1 million tonnes.

The ODA recognised early that an on-site supply of concrete would not only be a major benefit to meeting the London 2012 construction programme, but also could offer significant environmental benefits. The use of a single park-wide supplier with an on-site batching facility would minimise the risk of delays due to the security checks required for each incoming vehicle from outside the park. At the same time an on-site concrete plant offered significant sustainability gains as lower embodied energy mixes could be offered in bulk across the park. The adjacency of nearby rail lines would further reduce the embodied energy related to transport. Finally, an impressive 94% of all materials required for the concrete production on the Olympic Park site were able to be delivered to the batching plant by rail.

During the technical assessment of the tenderers for the on-site concrete supplier sustainability was weighted with 20% - significantly higher than typical assessments of 5% or less. Tenderers were asked to consider targets for recycled aggregate, cement substitution, sustainable transport of materials and low emission vehicles.

Whilst the ODA actively promoted the usage of pulverised fuel ash as cement replacement due to its wide availability in the UK, ground granulated blast-furnace slag as cement replacement is often preferred for visually exposed concrete due to its lighter colour. As a result both options were to be offered on-site to the venues.

The park wide targets set for cement replacement were set at minimum 40% PFA or 70% GGBS in all substructures and min. 30% PFA or 55% GGBS in all superstructures. In terms of aggregate substitutions the ODA set a target of min. 25% secondary aggregate compared to the 18% industry average then in London. Polycarboxylate superplasticizer admixtures were also to be used where feasible to reduce carbon emissions further as these reduce the amount of cement required.

The method of transportation played a key role in determining the source of the recycled (secondary) aggregate – WRAP guidance (Waste and Resources Action Programme, a UK based charity) promotes the use of primary aggregate when the source of secondary aggregate is more than 30 km further from the site if transported by vehicle.

Due to its wide availability and consistent quality the preferred source of recycled aggregate ultimately was stent, a china waste by-product from Cornwall, UK. Stent is a mined pozzolanic by-product of the Cornish clay industry, similar to metakaolin clay, and is used as a coarse aggregate. 110 tons of stent by-product is produced for each 1.1 tons of china clay. Due to the on-site rail connections, the aggregate was able to be transported by rail, thus the source of stent remained sustainable even so it had to be brought from 250 km further away than a nearby primary aggregate source.

Crushed recycled concrete was also used as an aggregate source. It came from concrete left on the park site over the years and concrete removed from projects within reasonable distances. Equally, mixed concrete returned to the batch plant was recycled for its aggregates.

Recycled aggregate accounted ultimately for 188,000 tons of the total, reducing the carbon footprint of the concrete by 33,069 tons and eliminating over 70,000 road vehicle movements.

Lastly, the on-site batching plant used recycled water to reduce the amount of potable water needed to mix concrete. This included concrete truck wash-out water and collected rainwater, resulting in a reduction of 9%.

The Aquatics Centre site is the most constrained on the Olympic Park, with a live railway to the east and the Waterworks River to the west. These constraints led to the parallel alignment of the three pools within the Aquatics Centre, as it was the only way they could fit on the site whilst accommodating the required seating numbers.

Table 1: Carbon saving substitution

	TOTAL PARK %	CEMENT/ AGGREGATE SUBSTITUTION (TONS)	REDUCED CARBON (TONS)
Cement substitution	32		15,652
Super plasticiser	7.3		9,810
Agg substitution*	21.9	186,290	
Reduced transportation	5.1		6,834
Park totals	24		31,967
Ready-mix agg		18,739	
Reclaimed water	9	4,125 M^3	

Source: Olympic Delivery Authority.

Figure 1: Aquatics Centre site with the underground power lines (picture by LOCOG)

Figure 2: Completed Aquatics Centre during the Olympic Games (picture by LOCOG)

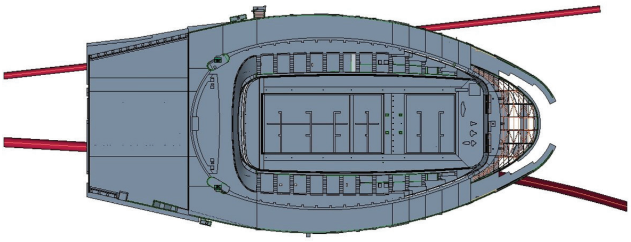


Figure 3: Building footprint above the underground power lines

Figure 5: Transfer Structure - largest pour in the Olympic Park: 1800 m3

To add to the complexity, two underground power lines carrying electricity to east London run under the length of the Aquatics Centre and a high groundwater table exerts a significant upwards force on the pools.

The underground power lines resulted in the need for very large transfer structures bridging over the tunnels. As a consequence the volume of concrete used for the Aquatics Centre exceeded by far this of other venues - in total 50,000 m^3 of concrete was utilised for its substructure and superstructure. Concrete was used for its foundations, the three pool tanks, the podium structure including its permanent seating tiers, three roof supports and even the diving boards.

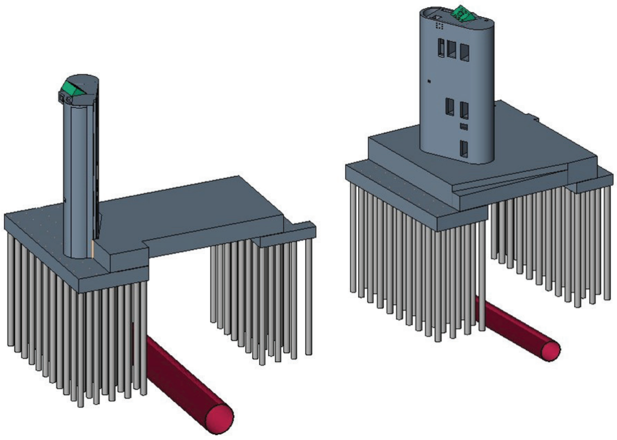


Figure 4: Below ground transfer structures underneath roof supports bridging over the power lines

Meeting the targets set by the ODA proved to be a significant challenge during the design and construction both in terms of cement replacement as well as in terms of recycled aggregate.

As large parts of the super structure on the Aquatics Centre were specified as visual concrete with the intention to remain exposed, GGBS mixes were specified for the superstructure, whilst PFA mixes were specified for the substructure.

On-site mock ups serving as quality benchmarks for visual concrete, showed that a high percentage of GGBS resulted in a much more difficult workability of the mix, which - in combination with the complex forms to be poured - did not deliver the quality of fair face concrete finish required. As a result an extensive series of trial pours was needed to establish the maximum percentage of GGBS that could be achieved, while still maintaining an excellent concrete finish.

The images on the next page illustrate these trials. Following trials with mixes ranging from 70 to 30% GGBS, the team finally settled on a 40% cement substitution for all visual concrete mixes. In order to still achieve the overall set target, cement

Figure 6: Concrete trial pours and quality control mock ups

replacement values of up to 70% PFA were utilised in areas of non-visual concrete.

Similarly the 25% target for the overall percentage of recycled aggregate could only be achieved by balancing an increased aggregate replacement percentage in the substructure against a decreased aggregate replacement percentage in the super structure.

As the waterproof concrete for the pool tanks required a virgin limestone aggregate with a lower thermal coefficient than stent to minimise the risk of cracking, the set target of 25% could not be achieved. In order to still meet the target overall within the project, the team increased the coarse aggregate substitution in other areas to up to 76%, setting a new benchmark and addressing concerns raised by other venues about the visual quality of concrete with aggregate substitutions. As a result other venues and infrastructures within the Olympic Park were subsequently successfully poured with 100% stent replacement aggregate.

The dedication of the team in maximising the sustainability of the concrete achieved over 4,000 tonnes of embodied CO_2 savings and substitution of over 29,000 tonnes of primary aggregate, equivalent to 28% of the total.

Ultimately, the Aquatics Centre exceeded the targets set by the ODA and was awarded an innovation credit under the Building Research Establishment's Environmental Assessment Methodology (BREEAM) assessment in recognition of their contribution to sustainable concrete construction.

Constructing the London Aquatics Centre has been an invaluable learning process for all those involved - clients, architects and contractors. Test pours and mock ups - essential for any high quality visual concrete, proved once again to be

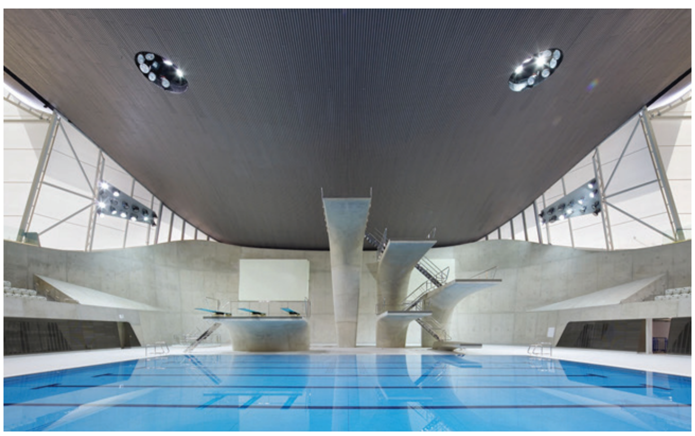


Figure 7: The completed Aquatics Centre including concrete dive platforms during the Games (Picture by Hufton + Crow)

Figure 8: The completed Aquatics Centre after the Games (picture by Hufton + Crow)

the key tool for achieving an equally high quality finish than with ordinary concrete.

Ultimately the sustainable construction of the London Aquatics Centre required a holistic approach considering all aspects and stages - from procurement to logistics, construction and finally disposal, all of which would not have been possible without the ambitious framework set out by the client in the first place.

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SARA KLOMPS has been with Zaha Hadid Architects (ZHA) for 21 years. She has held key roles on several major ZHA cultural projects throughout Europe and internationally, as well as various civic and infrastructure schemes. She is particularly interested in construction methodology and concrete design, and she lectures on these subjects regularly at architecture schools and industry events. She is registered as an architect in both the United Kingdom and Germany.

Cite this article: Klomps, S., (2021). “The use of sustainable concrete in the London Aquatics Centre”, *The Indian Concrete Journal*, Vol. 95, No. 5, pp. 7-11.

THE FUTURE OF CONCRETE AGGREGATES – A BRIEF REVIEW

I. G. AMADI,
M. G. ALEXANDER*,
H. BEUSHAUSEN

Abstract

An overview of the sustainability of concrete aggregates is presented. The paper highlights the growing demand for natural aggregates, especially sand and gravel, and the attendant environmental and socio-economic effects globally. Factors that may drive future aggregate demand are examined. These include, but are not limited to, transport and power infrastructure, land reclamation, and housing projects. The effect of urbanisation, population growth, and economic growth on aggregate consumption in the different regions of the world is also highlighted. Consequently, the use of recycled aggregates, crusher sand, and slag aggregates are considered as more sustainable alternatives to natural sand and gravel resources.

Keywords: concrete aggregates, sand and gravel, sustainability, recycled aggregate, crusher sand.

1. INTRODUCTION

Aggregates for concrete are generally referred to as granular materials, and typically comprise natural sand, gravel, or crushed rock, as well as recycled concrete and various industrial by-products such as metal slags. In addition to their use in concrete, aggregates also find vast use as construction materials for road pavements and land reclamation, support structures such as railway ballast, as well as in water filtration and sewage treatment systems. The most common use of aggregates is in the production of cement-based materials such as concrete and mortar. It is estimated that 40-50 billion metric tonnes of natural aggregate is mined annually, with over half this quantity used in the production of cement-based products [1-3].

Concrete and mortar are the most-used construction materials in the world. This status will likely continue for the foreseeable future as urbanisation, population growth and economic growth continue to drive the demand for concrete. The choice of concrete hinges on its durability, performance, adaptability to different environments, formability to different shapes, and near-universal availability of constituent materials.

Typically, aggregates constitute 60 – 75% by volume of concrete, and about 75 – 85% by mass, thereby making aggregates the most important constituent of concrete volumetrically, and also an important constituent technically [4]. Aggregates provide strength, stiffness, and dimensional stability to concrete. Additionally, aggregates contribute significantly to concrete durability as well as the reduction of the cost of concrete as they are typically cheaper and require less production energy than the other concrete constituents (except water). [5] report that the energy required to produce each ton of aggregate is approximately 20 times less than what is required to produce a ton of cement. Notwithstanding this importance, aggregates are often not the preferred area of research in concrete technology, with most research focusing on the binder phase – typically Portland cement, supplementary cementitious materials, and admixtures. One possible reason for this according to [4], is that engineering concrete to a specific performance requirement can largely be achieved through the intelligent manipulation of the binder phase.

Recently, discussions around concrete have increasingly focused on its sustainability. The major concern in this case is how to reduce the impact of concrete on the environment. As expected, Portland cement is central to the concrete sustainability challenge, given that the production of Portland cement contributes substantially to greenhouse gas emissions. For every ton of cement manufactured, approximately one ton of carbon dioxide is produced through the decomposition of calcite, fuel combustion during pyro-processing, electricity generation and transportation of materials [6]. Studies by [7] reveal that for the processing and manufacturing of constituent materials for concrete in South Africa, cement contributes 95% of the total CO_2 emission. To mitigate the environmental impact of cement - and by extension concrete production - low clinker cements as well as alternative binder materials and technology are being extensively developed. These include but are not limited to the use of limestone calcined clay cement (LC^3) [8], carbon capture, storage and utilization technology, use of slag and alkali-activated binders, and the use of belite- ye'elimite-ferrite (BYF) clinkers [6,9].

However, the environmental impact of concrete goes further than greenhouse gas emissions, as the depletion of natural constituent resources of concrete, particularly aggregates, has a profound effect on the environment. This is so given that

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extraction of aggregates impacts on the social and economic aspects of the communities where they are mined. This effect, though local, has become widespread in various regions of the world and therefore can be considered a global issue.
In light of this, the current paper provides a brief insight into the current impact of aggregate extraction on the world. The paper examines factors that are likely to drive aggregate demand in the foreseeable future. Sustainability, as defined by availability, environmental, social, and economic aspects of aggregate extraction, is also considered, and recommendations are made on the way forward.

2. ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACT OF AGGREGATE EXTRACTION

Historically, aggregates have been considered as a virtually infinite resource. This narrative was fuelled by the ubiquitous nature of aggregates, as found in quarries, rivers and alluvial beds, sand mines, marine sources, and the like. Substantial quantities of aggregates are now also produced from comminution of rock. Further, the relative ease of natural aggregate extraction, especially sand and gravel, when compared to other natural resources, means that aggregates are much cheaper [2] than many other natural resources. All these factors, in addition to the vast quantities of aggregates used, has given rise to what might now be considered an over-exploitation of this valuable resource. By way of example, presently, sand and gravel are extracted at a rate that is twice the rate at which aggregate sediments are deposited by all the rivers of the world [3]. This has given rise to environmental, social, and economic issues at local mining sites that have global consequences.

The nature of this problem varies with different regions around the world. In Asia, the hitherto abundant sand-bedded Lancang-Mekong river serves as a major source of aggregate to Vietnam, Cambodia, China, Thailand, Laos, Myanmar, and Singapore. These aggregates, which constitute about 90% sand and 10% gravel, are predominantly extracted at the lower end of the river situated in Cambodia and Vietnam [10]. Studies by [11] reveal that about 50 million tons of sand is being extracted from the river bed annually. This figure represents between 5 – 9 times the amount of annual sediments transported and deposited by the river. This has caused large cavities in the riverbed, measuring up to 8m depth, resulting in instability, earth movement and erosion around the riverbank, putting infrastructure at risk. The ecological impact is worsened by the presence of numerous dams along the length of the Lancang-Mekong river, which retain large amounts of sediments that ordinarily would have replenished some of the sand dredged from the riverbed [11,12]. The absence of clear legislation and regulatory policies restricting dredging activities on the river may have contributed substantially to these environmental issues. Additionally, the trans-boundary nature of the Lancang-Mekong river makes it difficult to achieve a consensus regulatory policy for the river resources as the adjourning countries have divergent interests [13,14].

In various parts of Africa and Asia, the existing natural aggregate resources have become strained and insufficient, leading to scarcity, illegal trade, and subsequent rise of 'sand mafias' and sand wars [15-17]. These criminal groups are responsible for the disappearance of beaches and islands in Morocco, India, Indonesia and Sri Lanka [18-20]. The heightened political tension between Singapore- the world's largest importer of sand for infrastructural development and territorial expansion, and its neighbours - Vietnam, Malaysia, and Cambodia, can largely be attributed to illegal sand trade [3,15,17,20].

In South Africa, environmental and socio-political issues occasioned by illegal and unsustainable sand mining have been reported along the coast and inland regions [21,22]. Illegal miners are responsible for the proliferation of large sand pits especially in the Limpopo and KwaZulu-Natal provinces of South Africa. These pits, which are often abandoned after sand extraction activities, constitute an environmental hazard to adjacent communities. Recently, a case of pit collapse was reported in Limpopo, killing two illegal miners [23,24].

In Rivers State in Nigeria, excessive sand dredging in the Akpajo, Chokocho, Choba, and Imo rivers is largely responsible for the scouring of bridge structures located along these rivers, see Figure 1. The fishermen in these communities have lost their sources of livelihood as the extraction of sand from the riverbed raises water turbidity which subsequently limits sunlight from supporting plant and animal life, leading to a loss of biodiversity in the river. Additionally, the noise and vibration from dredging equipment make it difficult for fish to breed and in some cases, fish are sucked up in dredging pipes.

Figure 1: Bridge scouring due to sand mining at Imo river in Rivers State, Nigeria, January 2021

It is evident that the excessive extraction of sand and gravel from terrestrial and marine sources negatively affect the communities where they are extracted. The nature and magnitude of this effect may vary across different regions of the world; however, the fundamental issue is, extraction of sand and gravel has a profound effect on the environment, social and economic aspects of the world.

3. FACTORS THAT WILL DRIVE AGGREGATE CONSUMPTION IN THE FUTURE

It is expected that the global consumption of concrete aggregates will increase for the foreseeable future as concrete remains the construction material of choice owing to its performance, versatility, and adaptability. Recent trends show that aggregate (coarse and fine) consumption has doubled over a 20-year period, from 20 billion tons per annum in 1998 to over 40 billion tons per annum in 2018 [1,2,25]. Additionally, future growth in population, the economy, urbanisation, and infrastructural demand, will significantly contribute to increasing aggregate demand.

According to [26], world population is projected to increase from 7.7 billion in 2019 to 8.5 billion in 2030, and up to 9.7 billion in 2050. Within this period, a steeper increase is expected for the population in urban areas. Urban population is estimated to increase from 4.2 billion (representing 55% of the world's population) to 5.17 billion (representing 60% of the world's population) in 2030 and then to 6.68 billion (representing 68% of world population) by 2050 [27]. The increase in world and urban population will necessitate the construction of infrastructural projects, especially in India, China and Nigeria, which together will account for about 35% of the urbanisation growth within the next 30 years [27]. Furthermore, economic growth will give rise to increased personal incomes and vehicle ownership, therefore intensifying the need for housing development and transport infrastructure [28, 29]. Consequently, these trends will give rise to increased aggregate demands.

Studies by [30] forecast that aggregate demand will rise by 2.3% per annum to 47.5 billion metric tons in 2023. In terms of market value, it is estimated that the average annual growth rate of 5.8% will raise global aggregate market value from USD 459 billion in 2019 to USD 723 billion by 2027 [29].

For the long run, the projected future consumption of aggregates may be difficult to quantify. However, a brief discussion is given below, of a few general landmark projects that will drive this consumption and provide insight of what is to be expected. It is worthy to note that most of the aggregates required for these projects may not be used for concrete production. Nonetheless, these competing alternative uses have direct impact on aggregate availability for concrete application.

3.1 Transport Infrastructure

The provision of transport infrastructure is expected to contribute markedly to the demand for aggregates in the future. Currently, about half the global aggregate consumption occurs in China, with an estimated annual consumption of aggregates at over 20 billion tons as of 2019 [31]. Ongoing mega-infrastructural transport projects include the Belt and Road Initiative (BRI) connecting China to Europe, Africa, and the rest of Asia. Another example is the 24 km eight-lane Shenzhen-Zhongshan bridge due for completion in 2024. According to [32], the total length of Chinese major highways more than doubled from 65 000 km in 2009 to 150 000 km in 2019. This trend is expected to continue for the foreseeable future, as more transport infrastructure is built, leading to a corresponding increase in aggregate production and consumption within the region.

Aggregate consumption in India, the second largest consumer of aggregate globally with an estimated consumption rate of 5.5 billion tons per annum, is expected to increase by 11% over the next 15 years [33]. This increase is driven by massive infrastructural transport developments, including airports, seaports, roads, bridges, and railway construction.

In the USA, the construction of the 1 285 km California high speed railway line is ongoing and expected to be completed in 2029. The Nigerian government is also undertaking massive railway projects within the country and on to neighbouring Niger Republic. Similarly, the 286 km Japanese Chuo Shinkansen high-speed rail line, which commenced in 2014, is ongoing. About 90% of this project will be underground or through tunnels [34], therefore significantly raising the aggregate demand for the project.

In South Africa, the upgrade of the 80 km N3 corridor connecting Durban to Pietermaritzburg, and the 55 km N2 stretch from Lovu River to Umdloti, is expected to commence soon [35, 36]. These highway expansions, which will include bridges and interchanges, will significantly raise the aggregate consumption in the Kwazulu-Natal province of South Africa where these projects are situated.

While the above-mentioned mega-infrastructure projects will generate large demand for aggregates, similar demands will be generated by on-going development of less spectacular but equally important transport projects all around the world.

3.2 Artificial islands

Artificial islands have become a norm around the world. These islands are built to meet infrastructural demands such as houses, airports, roads, oil rigs and power stations. Artificial islands can also be used to mitigate the effect of rising sea levels as well as serve as shoreline structures. The mode of construction involves depositing aggregates, especially fine aggregates, to reclaim land from the sea. While the use of concrete elements in the construction of artificial islands may be limited to protecting and stabilizing the sandfills, nonetheless, the enormous amount of aggregates (sand) required for these projects may significantly affect aggregate demand and availability in a given region. Consequently, this section will discuss a few artificial islands under construction or proposed for future construction.

The Wind Power Hub Island proposed to be built in the North Sea by 2030, will cover an area of about 6 km^2. This project, jointly funded by several European states, will provide wind farms which are expected to generate over 15 GW of electricity as well as the production of hydrogen gas for industrial application [37, 38]. It is estimated that about 128 million tons of sand will be required for the sand filling process. Subsequent expansion works which will increase the power generation capacity to over 100 GW by 2040 are proposed, thereby leading to increased aggregate demand.

In the United Arab Emirates, the Ghasha Artificial Island Construction Project is expected to include 10 artificial islands as well as provision of infrastructural access to these islands. The project, which is due by 2025, will require over 50 million tons of aggregates for land reclamation and concrete works [33, 39].

Hong Kong is proposing a 17 km^2 artificial island development by 2025, to address its housing deficit. This island which will require an estimated 260 million cubic meters of sand, is expected to be built largely with sand mined from the ocean and the neighbouring countries of Vietnam and Philippines [40-42].

The ongoing 10 km^2 Eko Atlantic City being built in Lagos, Nigeria, has already consumed about 90 million cubic meters of sand dredged from the Atlantic Ocean. Additionally, the 8 km long shoreline structure consist of a 9 m high wall, comprising boulders and concrete [43]. In Indonesia, tens of million tons of sand are being dredged from Sulawesi Island for the Makassar island reclamation project. The environmental consequences of this project have caused public outcry from the local population [44, 45]. Elsewhere, Singapore, a country which has increased its landmass by over 25% in the past 40 years, is continuing its territorial expansion by sand-filling the adjacent ocean using aggregates largely dredged from the ocean as well as imported sand from Vietnam, Malaysia, and Cambodia. The ongoing Sanya Hongtangwan and Xiamen Xiang'an airport projects being built on artificial islands in China have come at great cost in terms of capital and materials, and there are plans to expand these airports in the near future. This will further strain the aggregate resources within the region.

3.3 Other mega projects

The proposed third phase (Western route) of the South-North water project in China includes a canal with an estimated length of 450 km to be constructed. This canal is expected to convey about 8 billion m^3 of water per annum from the Yangtze river and its tributaries in the south, to the northern parts of the country.

Other mega projects that will drive aggregate demand include but are not limited to residential and commercial houses, dams, water filtration facilities, construction of power plants etc. These projects are expected to play a significant role in shaping the future of the aggregate industry.

4. MEETING FUTURE AGGREGATE DEMAND

To meet the enormous and ever-growing aggregate demand for the future, it is imperative that alternatives to natural sand and gravels be considered, given the finite nature of these resources as well as the sustainability issues associated with their extraction. Consequently, suitable alternatives to sand and gravel are discussed below.

4.1 Recycled aggregates

Recycled aggregates (RA) originate from construction and demolition waste (CDW) materials such as concrete, asphalt, and bricks. Typically, RA can be simplified as a two-phase composite material comprising the original natural aggregate (NA) and adhered binder material. For cement-based materials, RA comprises natural aggregate and adhered cement paste (ACP). This ACP, originating from the crushed concrete, contains hydrated and unhydrated cement in the mortar fraction. ACP may be weak and porous which reduces the density of RA, increases its water absorption, and raises the water demand of fresh concrete, thereby potentially negatively impacting on the mechanical and durability properties of concrete. This has limited the application of RA in the construction industry, as RA is generally deemed as inferior to natural aggregate. This therefore presents an opportunity for research, to engineer the properties of RA to meet concrete requirements for industry application.

The physical, chemical, and mineralogical properties of RA can be exploited according to the assertions of [4], where it was stated that harnessing aggregate properties can change the narrative of considering aggregates as inert constituents of concrete, to important input variables in the concrete matrix. The presence of unhydrated cement in the ACP of RA can promote the development of additional nucleation sites and formation of more hydration products thereby strengthening concrete and mortar [46, 47], especially in the long term [48, 49]. Furthermore, the hydrated cement phase of RA may contain calcium hydroxide [50, 51] which can raise the alkalinity and buffering capacity of concrete and mortar, thereby improving carbonation resistance, as well as activating the GGBS in slag-blended concrete, to hydrate and form more C-S-H gel. For RA concrete containing fly ash, studies have demonstrated that the cementing properties of the ACP in RA, especially fine RA, may have resulted in a pozzolanic reaction between the $Ca(OH)_2$ present in RA and the silica (SiO_2) present in fly ash, thus forming additional C–S–H and enhancing long-term strength [52-56]. When compared to virgin aggregate concrete, at ages beyond 28 days, RA concrete has a higher rate of improvement in strength properties.

Another method of engineering RA for use as large-scale replacement for natural aggregates is the use of limestone coating of RA. The process involves capturing CO_2 emitted from industrial processes such as cement plants, refineries, steel mills, natural gas, and coal-fired power plants, as well as capturing CO_2 directly from the atmosphere. This CO_2 then reacts with calcium which may be extracted from RA or other sources, to produce limestone ($CaCO_3$). The $CaCO_3$ is then used to coat RA [57, 58]. This improves the mechanical properties, shape, and texture of RA, thereby making it comparable to virgin aggregate. This technology, according to [58], has the potential to produce substantial aggregates to meet future demands. This is so given that the captured CO_2 requires no purification process before mineralization, unlike most industrial application for captured CO_2, thereby reducing cost and energy demand. Additionally, the enormous global aggregate demand will provide a viable market for this technology [58].

Generally, RA presents enormous benefits as a sustainable aggregate source for the future. RA can address the issue of scarcity and preservation of virgin aggregates as well as mitigate environmental concerns associated with extraction of virgin aggregates [59-61]. The use of RA will minimize the amount of CDW that is deposited in scarce landfills, thereby reducing disposal cost of construction waste [25, 60, 62-64]. Studies have also shown that recycled aggregate concrete (RAC) can substantially reduce the carbon footprint of buildings especially in the transportation phase, through the use of mobile recycling facilities, thereby reducing the carbon emissions associated with the haulage of natural aggregate [65]. Further, the technologies for separation and recovery of CDW are becoming relatively inexpensive with wide availability of recycled products [63, 65]. Thus, in most cases, recycled aggregate is relatively cheap compared with conventional virgin aggregate [64]. Other factors that may facilitate the increased use of RA for construction include: government legislation; increased availability of construction and demolition waste; recycling pressure by citizens; and population growth, which will increase infrastructural demand [25]. The benefits of RA are summarised in Figure 2.

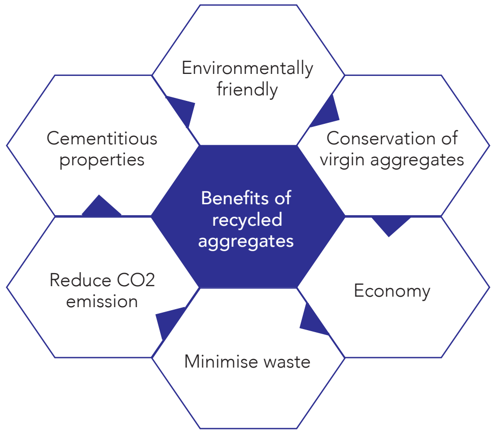

Figure 2: Benefits of recycled aggregates

Based on performance, environmental, social, and economic benefits, the use of RA as a partial replacement for natural aggregate is advocated. However, more research is required to enhance the properties of recycled aggregate concrete as well as the development of codes and specifications for recycled aggregate concrete. Additionally, government legislative policies are required to promote the large-scale integration of RA in concrete for industry application. These will ensure the sustainability of natural aggregate resources.

4.2 Crusher sand

Crusher sand results from the crushing of hard rock to produce fine aggregates. Depending on the crushing technology, parent rock and crushing condition, the crusher sand, which historically was not preferentially produced (as the focus was on coarse aggregate), can constitute up to 45% of the total crushed aggregate volume [66].

Presently, the increasing use of crusher sand in South Africa, India, China, and different parts of the world, is seen as a more sustainable alternative to the depletion and ecologically-undesirable extraction of river sand [33], as well as a solution to the legislative restrictions imposed on the extraction of river and pit sand [31]. For the Greater Cape Town area in the Western Cape Province of South Africa, [67] affirmed that sand resources have been tremendously depleted due to over-exploitation and competing land usage, urbanisation, agriculture, and natural protected land, all of which have necessitated the use of crusher sand in the local industry. Similarly, [5] reports that in Norway, the use of crushed rock aggregate is becoming predominant as sand and gravel use has declined from about 60% to less than 20% of the total aggregate consumption within the last 40 years.

Crusher sands can tend to be angular in shape, with rough texture and limited gradation, which tends to raise the water demand of the fresh concrete [66, 67]. Consequently, the crusher sand can be blended with the locally available river or pit sand to address these perceived shortcomings. Preferably, crusher sand should be produced with advanced crushing techniques that can help overcome these deficiencies, and produce sands which, in some cases, may have lower water requirements than the equivalent local sand. In the Cape Town area, the use of up to 60% crusher sand (usually from greywacke rock) as replacement for local sand in concrete application, is very common, and this is the case throughout much of the country, with little or no adverse effect on concrete water demand.

The relative availability of hard competent rock in most parts of the world will provide a viable feedstock for aggregate to meet the growing infrastructural needs. Furthermore, advancement in technology will allow for the crushing of rock to meet specific grading requirements, thereby reducing reliance on river and pit sand.

4.3 Slag aggregate

Hot molten slag is a by-product of the metal manufacturing process. Depending on the cooling process, coarse aggregates, fine aggregates, or very fine (ground) cement extenders may be produced. The use of certain slag aggregates, especially blast furnace slag, for asphalt and concrete application is well documented as they meet the specification in [68]. Studies by [69, 70] show that the physical, mechanical and durability properties of slag aggregate are comparable to natural aggregates. Consequently, slag aggregates are used as large-scale replacement for natural aggregates in concrete and asphalt applications without impairing performance.

From a sustainability perspective, the use of slag aggregates can be regarded as environmentally friendly as it limits the amount of slag waste that is deposited into scarce landfills. Additionally, slag aggregates require less processing energy in comparison to crushed rock and river sand aggregates. However, there is uncertainty about the distribution and future availability of slag aggregates around the world, for instance, the closure of a steel plant, with associated slag production, in the Western Cape Province of South Africa, has impacted local supply of this material.

5. ROLE OF GOVERNMENT IN DRIVING AGGREGATE SUSTAINABILITY

In light of aggregate scarcity, environmental issues associated with aggregate extraction, advancement in technology, health and safety regulations, governments around the world have become stricter with extraction guidelines and legislation for the aggregate industry. Companies will have to comply with strict guidelines on aggregate extraction in an environmentally responsible way that limits impact on the environment. Additionally, beyond the life cycle of pits and quarries, there must be plans to remedy the negative impact of the mining on the environment, as well as restoration action to recreate natural conditions and biodiversity [25, 71]. Measures to reclaim mining sites may include, but are not limited to, conversion of old quarries to wildlife parks, botanical gardens, residential homes, and water courses.

These guidelines and legislations are already being implemented in different parts of the world. The European Aggregate Association (UEPG) is promoting sustainability in the aggregate extraction industry by focusing on four key areas - biodiversity, water management, air quality and marine aggregates [72]. The overarching goal is to make the European Union a climate neutral continent by 2050. Elsewhere, [31] notes that the introduction of strict new environmental quarrying standards is impacting the aggregate industry in China. Small mining companies are either closing or consolidating to enable them to comply with the Chinese government guidelines.

6. CONCLUSION

Aggregates are essential and important constituents of concrete and mortar that contribute significantly to their properties. The high demand for concrete and mortar has led to unsustainable mining and subsequent depletion of natural aggregates, particularly sand and gravel resources, thereby impacting the environment, economic, and social aspects of communities and, by extension, the entire globe. Notwithstanding, future demand for aggregates is expected to grow, largely driven by population growth, urbanisation, economic growth, transport infrastructure development, creation of artificial islands, and other mega projects. This further raises questions about the sustainability of natural aggregates.

Consequently, alternatives to sand and gravel are required, and have been briefly discussed in this paper. This includes the use of recycled aggregates, crusher sand, and slag aggregates. Studies have shown that the physical, chemical, and mineralogical properties of recycled aggregate can be harnessed to meet concrete requirements for industry application. Also, CO_2 captured from industrial processes and the environment, can be used to enhance the properties of recycled aggregates. Therefore, recycled aggregate may be more economical, with less environmental impact when compared to natural aggregate.

The use of crushed rock as coarse and fine aggregate offers a viable source for future aggregate resources, as it is already widely used in South Africa and other parts of the world. The relative availability of hard competent rock in most parts of the world will provide a viable feedstock for crushed aggregate to meet growing infrastructural needs. Furthermore, advancement in technology will allow for the crushing of rocks to meet specific grading requirements, thereby reducing reliance on natural sand and gravel, as well as mitigate the environmental issues associated with river sand and gravel, as well as pit sand extraction.

From a performance perspective, certain slag aggregates, especially blast furnace slag, are comparable to natural aggregates in terms of properties and performance. Additionally, such aggregates are environmentally positive, as they may require less processing energy than natural aggregates, and they also reduce the amount of waste deposited in scarce landfills. However, limited availability across the world is a concern.

The role of government in ensuring sustainability in the aggregate industry is also highlighted. It is imperative that guidelines and legislations are crafted and adhered to, in order to ensure that aggregates are extracted in an environmentally responsible way that limits impact on the environment. Additionally, beyond the life cycle of aggregate extraction sites, there must be plans to remedy the negative impact of mining on the environment. Furthermore, governments should enact policies that promote large-scale industry application of alternatives to natural sand and gravel.

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Cite this article: Amadi, I. G., Alexander, M. G., Beushausen, H. (2021). "The future of concrete aggregates – A brief review", *The Indian Concrete Journal*, Vol. 95, No. 5, pp. 12-21.

FEASIBILITY OF USING RECYCLED CONCRETE AGGREGATES TO PRODUCE ULTRA HIGH PERFORMANCE CONCRETE: A PRELIMINARY STUDY

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Abstract

This paper presents a preliminary feasibility study on the utilisation of a high quality recycled concrete aggregates (RCAs) to manufacture ultra high performance concrete (UHPC), which represents a new type of cementitious material having superior workability, mechanical performance and durability properties in comparison to conventional concrete. The particle size of the RCA used in this paper ranges from 4 to 8 mm. A total of 4 mixtures are made in the test program, which include a reference mixture with natural coarse grains and 3 mixtures with RCA as coarse aggregates. Since the RCA has high water absorption, the incorporation of this material in producing concrete requires a compensation of the water demand to achieve the desired workability. In the 3 concrete mixtures with RCA, different compensation water amounts are added. Laboratory tests on the workability, compressive strength, modulus of elasticity and four point bending behavior of the concrete mixtures are carried out. The test results indicate that it is possible to use RCA to produce UHPC despite that its incorporation results in some reductions in the mechanical properties of the concrete mixture in comparison to the reference UHPC mixture with natural coarse aggregates.

Keywords: Recycled concrete aggregates (RCAs), ultra high performance concrete (UHPC), water absorption, workability, strength, deformation.

1. INTRODUCTION

Recycled concrete aggregates (RCAs) are produced by processing end-of-life (EOF) concrete. In the past decades, many research efforts have been devoted to find applications for that material. Based on the research results, it is more and more accepted that RCAs represent a valuable material with a lot of potential in manufacturing construction products although their properties are in general lower than that of natural aggregates [1]. Up to now, the main research on using RCAs has been focused on producing new concrete. With the increased recognition of the intrinsic value of the material, attempts on incorporating RCAs in structural concrete have been made by many researchers [2-5]. More recent research results indicate it is even possible to manufacture high strength/high performance concrete (HSHPC) with RCAs [6-11]. Generally, no key obstacles in the production of HSHPC with RCAs have been found despite that the mechanical and durability properties of concrete incorporating RCAs are in general lower than that of conventional concrete with natural aggregates.

Belgium has a long history of recycling concrete and valorizing RCAs in engineering practice [12]. Now the recycling industry in Flanders, Belgium has become a well developed industry. The experience indicates that it is wise to find suitable applications for recycled materials based on their quality to achieve a more efficient utilisation of the resources. According to the European especially the Belgian practical experience, through processing demolished concrete from road surface layer (compressive strength ≥ 50 MPa) using a two-stage crushing process, a high quality RCA can be produced. The resulted RCA has an enhanced quality in comparison to the Type A RCA in EN 206 [13] and meets the requirement in NBN 15-001 [14] for RCA of Type A+. It is thus very interesting to search for high grade applications for that material. In a previous research work [15], the test data revealed that it is feasible to develop HSHPC up to a strength class of C80 with that type of RCA without adding any mineral additions.

The development in modern concrete technology benefits to explore the possibilities of using RCAs as a secondary raw material to substitute natural aggregates in practice. Ultra high performance concrete (UHPC) represents one of the most significant advances in concrete technology in recent years. This material has a very dense structure with superior workability, mechanical properties and durability performance,

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permitting the construction of both more slender and more durable concrete structures with a prolonged service life and enhanced sustainability [16]. In the early stage of research on developing UHPC, no coarse grains (particle size > 1 or 2 mm) were incorporated [17]. Later, it was found that it is possible to include coarse grains up to 8 mm in producing UHPC [18]. In fact, the incorporation of coarse grains can lead to some benefits such as limiting the shrinkage and creep deformation of the concrete. A UHPC mixture with particles of maximum size 8 mm was developed by Hoang [18] with excellent material properties.

The objective of this paper is to examine whether it is possible to replace the coarse grain 4-8 mm in the UHPC mixture with high quality RCA of the same fraction. In conventional UHPC mixture with coarse grains, basalt is often used in order to increase the compressive strength of the concrete. However, basalt is not available in Flanders, Belgium. This practical situation motivates the present research. In a previous study, the possibility of using the fine fraction of RCA as a replacement of natural sand in UHPC was evaluated [19]. However, no research work on incorporating the coarse fraction of RCA in UHPC was found in the literature. Some test results derived from this study have been briefly reported in [20]. In this paper, more detailed information is presented.

2. TEST PROGRAMME

2.1 Materials

The materials used in this study include CEM I 42.5 R (C3A free) confirming to EN 197 [21], micro-silica fumes, quartz powder, sand (GEBA) 0-0.25 mm, sand (Dorsilitnr. 8) 0.125-0.50, sand 1-1.8 mm, basalt 4-8 mm and RCA 4-8 mm, tap water, Prement H 500 H 500 def 2 superplasticizer and steel fibers (length: 13 mm, diameter: 0.16 mm).The RCA was produced by a local recycling plant in Flanders, Belgium. Figure 1 presents the photos of some of the used materials. The particle size distributions of all aggregates are given in Figure 2. The physical properties of the RCA including the apparent density ρ_a, oven dry density ρ_{rd} and saturated surface dry (SSD) density ρ_{ssd} and the 24h water absorption WA_{24} can be found in Table 1.

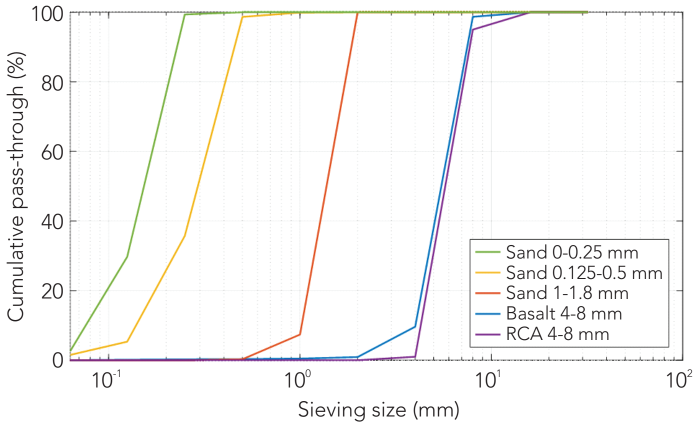

Figure 2: Particle size distribution

Table 1: Properties of coarse aggregates

AGGREGATE	ρ_a (kg/m³)	ρ_{rd} (kg/m³)	ρ_{ssd} (kg/m³)	WA_{24} (%)
Basalt 4-8 mm	2910	2890	2890	0.3
RCA 4-8 mm	2650	2360	2470	4.7

2.2 Concrete mixtures

As mentioned above, the objective of this study is to examine the substitution of the basalt 4-8 mm with RCA on the properties of the UHPC mixture. For this purpose, a total of 4 concrete mixtures are designed in this study. The reference mixture, which contains only natural coarse grains (4-8 mm) is based on the mixture developed by Hoang [18], where the coarse fraction accounts for 25.2% of the total aggregates (in volume). The high quality RCA is used to fully substitute the basalt fraction. Since the water absorption of the used RCA is significantly higher than that of the basalt, a compensation of the mixing water is required in order to minimise the negative effect of the RCA on the workability of the mixtures. However, the determination of the exact amount of the compensation water is a difficult task, although it is commonly determined according to the full

(a) Basalt 4-8 mm (b) RCA 4-8 mm (c) Sand 1-1.8 mm (d) Steel fibres

Figure 1: Some materials used in this study

Table 2: Mix proportions (kg/m^3)

	U-NA	U-RCA50	U-RCA75	U-RCA100
Cement CEMI 42.5R	650	650	650	650
Micro-silica fume	195	195	195	195
Quartz powder	84.5	84.5	84.5	84.5
Sand 0-0.25 mm	128	128	128	128
Sand 0.125-0.50 mm	345	345	345	345
Sand 1-1.8 mm	483	483	483	483
Basalt 4-8 mm	371	0	0	0
RCA 4-8 mm	0	273	273	273
Water	162.5	162.5	162.5	162.5
Compensation water	0	6.6	9.8	13.1
Superplasticizer	19.5	19.5	19.5	19.5
Steel fiber	39.3	39.3	39.3	39.3

water absorption of 24 h [2]. In this paper, the compensation water is calculated based on 50%, 75% and 100% of the 24h water absorption of the RCA, respectively. Table 2 presents the 4 mixtures designed in this study. Mixture U-NA represents the mixture with natural aggregates (as the reference) while the Mixture U-RCA50, U-RCA75 and U-RCA100 indicates the mixture incorporating RCA and with 50%, 75% and 100% compensation of the 24h water absorption of the RCA. For all the 4 mixtures, the fibre content is 0.5% (volume).

2.3 Specimen preparation

All concrete mixtures are produced using a Cyclo mixer (shown in Figure 3) in the laboratory with the following mixing procedure: firstly, the cement, micro-silica fume, quartz powder, and water are mixed rapidly for 2 minutes followed by a mixing break for 2 minutes; then the superplasticizer is added during

Figure 3: Mixer used in this study

Figure 4: Casting of specimens

the running of the mixer with a duration for 2 minutes (until the mixture becomes liquid); after that, the mixer is opened and the mixtures attached to the cover and wall of the mixer are scraped off and the mixture is mixed for another 4 minutes; then the sand is added followed by a mixing duration for 5 minutes; finally, the steel fibres are added into the mixture and then a mixing for another 1 minute is followed. Upon the mixing, the consistency of the concrete mixtures is measured. After that, the mixtures are cast into steel moulds. Figure 4 shows the casting of the test specimens. No vibration is needed since all the mixtures have self-compacting properties. The specimens are demoulded after 24 hours and then cured under warm water at a temperature of 80°C. After that, they are cured for another two days in a climate room at 20°C and 95% RH before tests on the specimens are carried out.

2.4 Test methods

The consistency of the fresh mixed UHPC mixtures is evaluated by the slump flow test according to EN 12350-8 [22]. The fresh mixture is placed into a Haegermann cone. The cone is then lifted to allow a smooth flow of the mixture. After two minutes, the diameters of the concrete mixtures in two perpendicular directions are measured and their mean value (d_m) is recorded as slump flow value. In addition, the parameter t_{200} for each concrete mixture, which is the time required for reaching a slump flow of 200 mm is also measured.

For each concrete mixture, a total of three 100 mm cube and three cylinder specimens (diameter: 100 mm, height: 200 mm) are cast. They are used to measure the cube compressive strength and modulus of elasticity of the concrete mixtures according to EN 12390-3 [23] and EN 12390-8 [24], respectively. After the modulus of elasticity test, the cylinder specimen is loaded until failure to derive the cylinder compressive strength of the concrete. For the mixtures U-NA and U-RCA50, two and three beam specimens (50 × 150 × 600 mm^3) are also cast,

Figure 5: Test setup for four-point bending tests

Figure 6: Some typical specimens after demoulding

respectively. The specimens are tested under four-point bending according to SIA 2052 [25] by means of the test setup shown in Figure 5. During the bending test, the load and the mid-span deflection of each specimen is recorded. In Figure 6, some typical specimens prepared in this study are given.

3. TEST RESULTS

3.1 Fresh properties

The measured slump flow (d_m) and t_{200} for each concrete mixture are given in Table 3 and Figure 7, Figure 8 shows the flow of the concrete mixtures U-NA and U-RCA100. It can be seen from the table that the incorporation of the RCA affects the consistency of the concrete mixture; however, the effect depends on the amount of the compensation water added into the mixture. When 50% of the 24h water absorption of the RCA is compensated, the d_m–value and t_{200} are comparable to that of the reference mixture; as the amount of the compensation water increases, the measured d_m–value increases while the t_{200} decreases. The variation in the d_m and t_{200} is mainly attributed to the increase of the mixing water. Moreover, the shape of the RCA can also have an effect on the flowability of the mixtures. Both the RCA and basalt have an angular shape. During the mixing, the sharp angles on the RCA can be pulverized, while the basalt is much stronger and remains its angular shape. As a result, the smoothing of the RCA shape can benefit the flow of the concrete mixture. This can help to explain why a 50% compensation of the water absorption of the RCA yields similar d_m and t_{200} between the mixture with RCA (i.e. U-RCA50) and reference mixture.

Table 3: Measured properties of the concrete mixtures

MIXTURE	d_m (cm)	t_{200} (s)	f_{cu} (MPa)	f_{cyl} (MPa)	E_c (MPa)	$f_{ct,fl}$ (MPa)
U-NA	25.7	16	192.0	187.3	55 823	11.48
U-RCA50	24.9	15	177.6	160.3	52 818	9.99
U-RCA75	27.8	9	164.8	149.3	52 522	-
U-RCA100	27.5	8	164.5	160.1	52 883	-

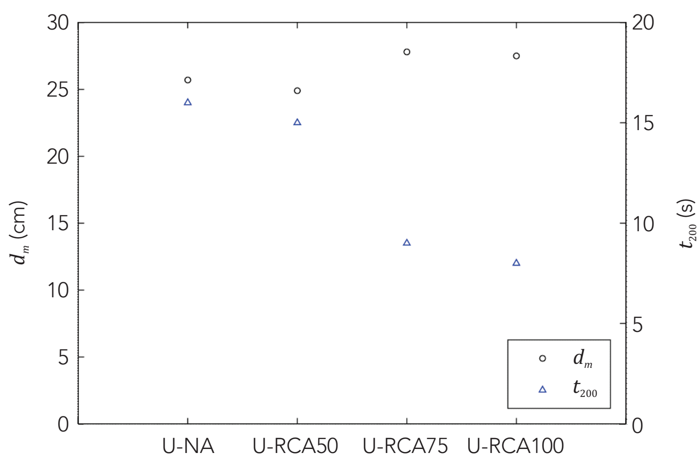

Figure 7: Measured slump flow (d_m) and t_{200}

(a) U-NA

(b) U-RCA100

Figure 8: Slump flow test

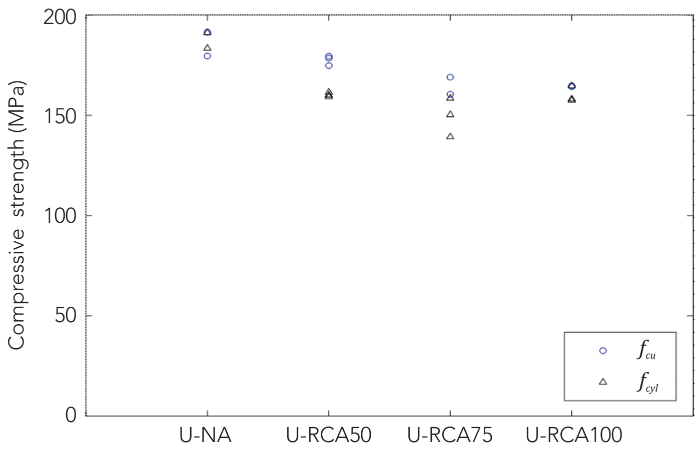

Figure 9: Compressive strength of the concrete mixtures

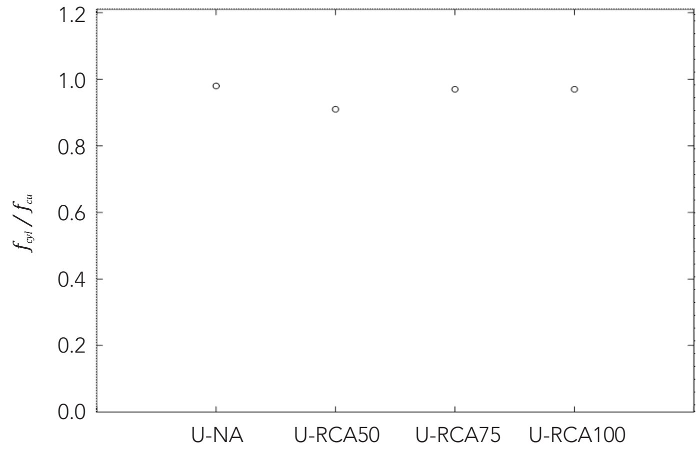

Figure 10: f_{cyl}/f_{cu} – ratio of the concrete mixtures

3.2 Compressive strength

The measured cube and cylinder compressive strength, f_{cu} and f_{cyl}, of the concrete mixtures are given in Table 3 and Figure 9. The figure reveals that the incorporation of the RCA in the concrete mixture results in a decrease of both of the cube and cylinder compressive strength. However, the reduction in the compressive strength is found to be dependent on the amount of the added compensation water. The reference mixture exhibits a f_{cu} and f_{cyl} of 192 MPa and 187 MPa, respectively. When the compensation water is calculated based on 50% of the 24h water absorption of the RCA, the concrete has a f_{cu} of 177 MPa and f_{cyl} of 163 MPa, implying a reduction in the compressive strength of 8 and 13%, respectively. It seems that the decrease of f_{cyl} is more pronounced than f_{cu}.

An increase of the compensation water to 75% of the 24h water absorption results in a further decrease of the concrete compressive strength. The reduction of f_{cyl} is, however, comparable to that in f_{cu}, which is 15% and 14%, respectively. The further increase of the compensation water to 100% does not result in a further decrease of the compressive strength of the mixture.

The decrease of the compressive strength for concrete incorporating the RCA is obviously due to the lower quality of the RCA in comparison to the basalt. It is generally accepted that the use of RCA in concrete increases the porosity of the microstructure of the concrete, which has a negative effect on the compressive strength. In addition, the addition of the compensation water can alter the effective water/binder ratio, thus resulting in a variation of the compressive strength. However, the reduction in the compressive strength of the concrete mixtures due to the incorporation of RCA is limited to 15%. This is because the volume of the coarse grains in the concrete mixture is relatively low, which accounts for only around 25.2% of the total aggregate volume.

Figure 10 shows the f_{cyl} / f_{cu}– ratio for each mixture. It is found that that ratio for UHPC with RCA does not differ much from that for the reference UHPC mixture. Since the f_{cyl} / f_{cu} – ratio is often related to the brittleness of the concrete materials, the above results indicate that the use of RCA does not significantly affect the brittleness of the material.

3.3 Modulus of elasticity

The modulus of elasticity E_c of concrete is an important parameter, which describes the deformation behavior of the material. UHPC exhibits an increased modulus of elasticity in comparison to normal strength concrete [16]. The measured E_c for each concrete mixture is shown in Table 3 and Figure 11.
It is clear that the incorporation of the RCA results in a decrease of the modulus of elasticity of the mixture. It is widely accepted that the use of RCA reduces the E_c of concrete since the modulus of elasticity of RCA is smaller than that of natural aggregates. The test data in Figure 11 implies that the E_c of the mixture with RCA is 5 - 6% lower than that of the reference UHPC mixture, which is 55 800 MPa.

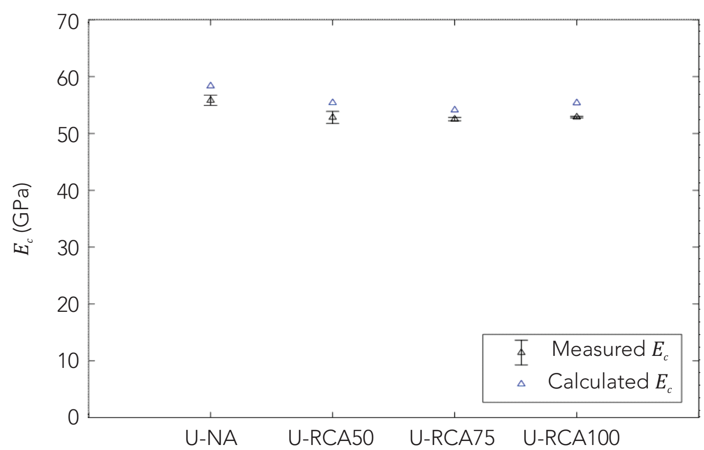

Figure 11: Elastic modulus of the concrete mixtures

In previous study, an empirical equation for estimating the E_c was proposed by Ma [26], as

$$E_c = 10200\, f_{cyl}^{1/3} \quad (1)$$

In Figure 11, a comparison of the predicted and measured E_c for each concrete mixture is given. It can be observed that Equation (1) gives a slight overestimation of the measured E_c for both the concrete mixtures with and without RCA.

3.4 Flexural behavior

The measured load - mid span deflection curves for the beams of the concrete mixture U-NA and U-RCA50 are shown in Figure 12. It can be seen from Figure 12 that the incorporation of the RCA influences the flexural behavior of the beams. When the RCA is used, the maximum force F_{max} of the beams decreases from 7.63 to 6.53 kN. It can also be seen from Figure 12 that the post-cracking behavior of the beams with and without RCA is generally similar. Table 4 presents some characteristic values of the concrete mixtures derived from the load – mid span deflection curves, including the maximum force F_{max} and its corresponding mid-span deflection δ_{max}, the residual forces corresponding to a mid-span deflection of 0.5 mm and 3.5 mm, $F_{0.5}$ and $F_{3.5}$, respectively. It can be observed from the table that the use of the RCA affects the ratios of $F_{0.5} / F_{max}$ and $F_{3.5} / F_{max}$. In general, the beams with the RCA exhibit lower $F_{0.5} / F_{max}$ – ratio while higher $F_{3.5} / F_{max}$ – ratio.

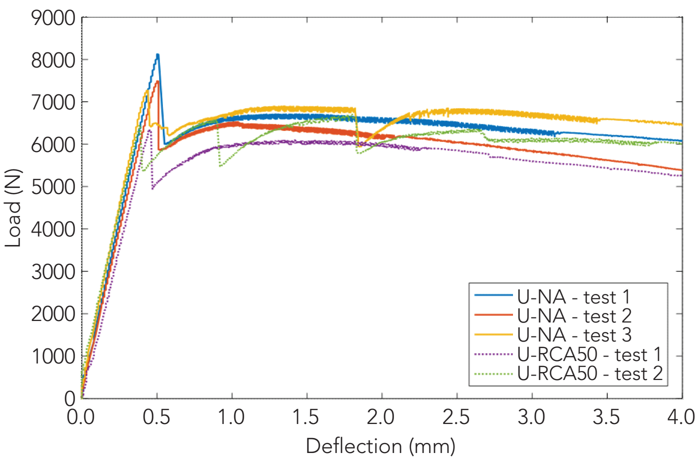

Figure 12: Load-mid span deflection curves of beams

By using Equation (2), the flexural tensile strength $f_{ct,fl}$ of the concrete mixture can be determined.

$$f_{ct,fl} = \frac{F_{max} l}{bh^2} \quad (2)$$

in which, F_{max} is the maximum force (N); l is the span of the beam (= 450 mm); b is the width of the beam (= 150 mm) and h is the height of the beam (= 50 mm).

It is found that the flexural tensile strength of the mixture U-NA is 11.48 MPa; while for the mixture U-RCA50, it is 9.99 MPa, as shown in Table 3. The latter is about 87% of the former, indicating that the incorporation of the RCA reduces the flexural tensile strength of the concrete mixture.

4. CONCLUSIONS AND REMARKS

This paper presents a preliminary study on the use an industrially produced high quality coarse RCA (4 – 8 mm) to manufacture UHPC. Within the scope of this study, the following conclusions can be drawn:

- It is possible to produce UHPC with the high quality RCA although the incorporation of this material results in a decrease of the compressive strength;
- The consistency of the concrete mixture with RCA depends on the amount of the compensation water owing to its high water absorption. When a 50% compensation water is added, the slump flow d_m and t_{200} of the mixture is comparable to that of the reference UHPC mixture; a further increase of the amount of the compensation water further enhances the flowability of the concrete mixture;
- The amount of the compensation water also affects the variation in the compressive strength compared to that of the reference UHPC mixture. Up to an amount of 75% of the compensation water based on the 24h water absorption, the compressive strength of the concrete decreases with the increase of the compensation water. A further increase of the amount of the compensation does not result in a further decrease of the compressive strength;
- The modulus of elasticity of concrete mixtures with RCA is 5-6% lower than that of the reference UHPC mixture;

Table 4: Results of four-point bending tests

MIXTURE	F_{max} (kN)	δ_{max} (mm)	$F_{0.5}$ (kN)	$F_{3.5}$ (kN)	$F_{0.5} / F_{max}$	$F_{3.5} / F_{max}$
U-NA-test 1	8.12	0.50	8.12	6.22	1.00	0.77
U-NA-test 2	7.49	0.50	7.49	5.62	1.00	0.75
U-NA-test 3	7.27	0.44	6.49	6.60	0.89	0.91
U-RCA50-test 1	6.36	0.45	5.08	5.44	0.80	0.86
U-RCA50-test 2	6.71	0.39	5.72	6.11	0.85	0.91

- The flexural load- mid span deflection behavior of concrete mixture with RCA is similar to that of the UHPC reference mixture. However, the use of the RCA reduces the maximum flexural load and thus the flexural tensile strength, while tends to enhance the residual tensile behavior of the beams.
- More research work is required to investigate the mechanical and durability performance of UHPC mixtures incorporating the RCA.

5. ACKNOWLEDGEMENTS

This research work has been supported by a start–up funding of KU Leuven (No. STG/16/011), the Han & Li Chair in Smart and Sustainable Infrastructure and Zero-Waste in Construction at KU Leuven, and the Erasmus+ staff mobility project between KU Leuven and TU Graz. All the financial supports are gratefully acknowledged. The authors would also like to express their sincere thanks to Dipl.-Ing. Michael Huß, Dr. techn. Kim Hoang and Prof. Dr.-Ing. habil. Nguyen Viet Tue of Institute for Structural Concrete, TU Graz for providing the precious supervision and necessary assistance in this research work.

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Cite this article: Sierens, Z., Joseph, M., Li, J. (2021). "Feasibility of using recycled concrete aggregates to produce ultra high performance concrete: A preliminary study", *The Indian Concrete Journal*, Vol. 95, No. 5, pp. 22-29.

EFFECT OF AGGREGATE GRADING ON THE FRESH AND MECHANICAL PERFORMANCE OF RECYCLED AGGREGATE SELF-COMPACTING CONCRETE

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PASLA DINAKAR*

Abstract

Due to the substantial boom in infrastructure growth in developing countries such as India, the supplies of natural aggregates (NAs) are declining at a high rate and thereby causing an ecological imbalance. Contrary to that enormous volume of recycled aggregates (RAs) created from the waste of building and demolition (C&D). Therefore, in terms of preservation, the use of RA in the construction of reinforced concrete can be a great source of aggregate. It is well known that aggregates occupy nearly 70 percent of the volume in concrete, and they help in optimizing the cement and water and thus enabling higher strengths while lowering the shrinkage, creep, and temperature effects in concrete. The shape, size, grading, and texture (of natural, artificial, and recycled types) affects the water needed for certain workability considerably. The grading and proportions of the individual coarse and fine aggregates (either in all-in aggregate grading or otherwise) affects workability and this influence is more pronounced when self-compacting concrete is used. In the present investigation, self-compacting concrete (SCC) was developed with complete substitution of coarse NAs with coarse RAs by employing the all-in aggregate grading curves of DIN standards. Supplementary cementing materials (SCMs) such as coal fly ash (CFA), ground granulated blast furnace slag (GGBS), and metakaolin (MK) have also been used as cement substitute materials to make the SCC more sustainable. Finally, based on fresh properties such as slump flow, T500, V-funnel, and L-box test, and mechanical properties through compressive strength test, a comparison is made for concrete with the use of DIN combined grading against the all-in grading curve defined in the BIS code. It is concluded that, especially in the presence of SCMs, the DIN all-in aggregate grading provides better workability and mechanical performance for SCCs compared to BIS all-in aggregate grading method.

Keywords: Self-compacting concrete; recycled aggregate; Combined grading, DIN standard, GGBS; fly ash; metakaolin;

1. INTRODUCTION

The cement and building industries are providing more focus on sustainability in this new age. In the construction industry, the use of Recycled aggregate (RA) could be a move forward in the development of a sustainable environment since it decreases not only the consumption of natural aggregate(NA) but also reduces the land requirement for filling of concrete debris resulting from the demolition of buildings, bridges, etc. In the last two decades, research on the mechanical and durability properties of recycled aggregate concrete (RAC) members has been widely investigated. RA containing attached mortar is culpable for the less consumption of RA as that reduces the mechanical and durability performance of resulting RAC [1-9]. Recent findings on RAC have shown that physical treatment such as thermal treatment and chemical treatment such as carbonation, acid soaking of RAs can be undertaken to decrease the amount of mortar attached. In addition, by incorporating supplementary cementitious material (SCM) such as coal fly ash(CFA), GGBS, rice husk ash, silica fume (SF), metakaolin (MK), etc. into the mixture, the characteristics of RAC were greatly improved [10-17].

In SCCs, a limited analysis was carried out concerning the use of RAs in SCC. The effect of RAs on SCC properties was investigated by Pereira-De-Oliveira *et al.* [18] and Grdic *et al.* [19] and noted that the addition of RAs significantly diminished the workability and mechanical performance of the SCC. V-funnel flow time increases with the addition of RA because of its rougher exterior compared to NA [20]. On the other hand, Uyguno'lu *et al.* [21] observed that SCC affected by RA had lesser flow times relative to NA. This is due to the fact that being lighter, RA moves smoothly in SCC. Tuyan *et al.* [22] stated that with the addition of RA, capillary water absorption value increases, while Pereira-De-Oliveira *et al.* [18] reported a contradictory finding, reporting that the incorporation of RA reduces the absorption of capillary water by up to 12 percent for 100 percent RA owing to thick cement paste.

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Grdic *et al.* [19] reported that for 100% RA replacement with NA, the overall amount of permeable voids increased by 67 percent when analyzing water absorption by immersion. Kou and Poon [23] further found that the chloride migration resistance was reduced with further inclusion of RA. The effect of various replacement levels of CRAs on the compressive of high strength SCC was evaluated in another study by Fakitsas *et al.* [24], and they stated that CRAs had higher strengths comparing to natural aggregate concrete (NAC). The replacement of NAs with CRAs in a similar study by Kebaïli *et al.* [25] severely impacted the self-compacting properties of CRAs due to the angular form and rougher surface of CRAs because of the attached mortar. Carro-López *et al.* [26] previously evaluated the rheological activity of SCC with recycled fine aggregates (RFAs) and found that- all SCC mixtures had stronger self-compacting properties and higher compressive strength of up to 20 RFAs with natural sand replacement. Khodair and Bommareddy tested the properties of different SCC mixtures of various SCMs, such as fly ash and slag, and found that the mechanical properties are reduced by increasing the substitution of CRA. However, the compressive strength was diminished when SCMs partly substituted cement, but the hardness tolerance of SCC mixtures was greatly improved. By combining recycled coarse and fine aggregates (FRA), Kou and Poon [23] tested different SCC properties, such as fresh, mechanical and durability criteria, and concluded that both CRA and FRA can be used for the processing of SCCs. Singh and Arya [27] measured SCC's mechanical and durability characteristics, integrated with MK as a substitute for OPC and coal bottom-ash as a substitute for natural fine aggregate(NFA), and revealed that integrating MK into the system enables to generate SCC by replacing NA with RA entirely.

As far as the development of SCC is concerned, the key factors are good quality of material, mixing in correct proportions, adopting the right all-in aggregate grading, and preserving the water/powder ratio in order to sustain SCC's flow capacity, workability & strength. Either by absolute volume method or by weight method, an appropriate ratio of the fine aggregate to total aggregate is calculated based on the maximum size of the coarse aggregate and the grading of the fine aggregate (as in the case of ACI and BS), while the all-in grading of the total aggregate is ensured in the DIN [28] and BIS [29] standards.

To sum up, detailed research using RA in standard concrete has been performed. Nevertheless, the experiments linked to show the efficiency of all-in grading through DIN standard and BIS codes for SCC integrated with 100 percent CRA replacement, especially with different SCM replacement levels, were not analyzed yet. The present research is an effort in this direction.

2. IMPORTANCE OF AGGREGATES GRADING

The strength and performance of concrete depend primarily on the quality of cement used, water, aggregates, and proportioning constituents. Apart from this, the distribution of grading of the aggregate fillers influences both performances and, more importantly, in engineering the material's cost. There should be a minimum volume of fine aggregate below which the workability of concrete will be inadequate (too stiff) and a maximum to avoid concrete segregation. An increase in finer particles (sand or cementitious material) can ensure better packing and better flexibility. But this increase in fines content will also mean a higher surface area required to be wetted. It will need higher water contents resulting in higher cement contents at the same water-cement ratio, by which the concrete will become uneconomical. Hence, it is necessary to provide an optimum grading requirement for specific workability and type of concrete [30].

Generally, in most natural specifications, the fine aggregate is taken to be a certain fraction of the total aggregate based on the maximum size of the coarse aggregate. It is well known that both the aggregates will have to be well graded. The other method is to adopt an all-in grading for all the aggregates, which will ensure the appropriate distribution of all the sizes involved. This will also help in a better filler effect while ensuring reasonably lower water requirements and better strengths [30].

As far as the CEB-FIP [31] code of practice is concerned, it clearly states that the aggregates consist of a mixture of particles of different sizes which are combined in accordance with specific requirements. The principle aspects concerning the overall aggregate grading can be summarized as follows.

- To arrive at the maximum particle size depending on the dimensions of the member, thickness, concrete cover, spacing of reinforcement and handling and placing conditions.
- To have sufficient workability for the compaction adopted with optimum content of fines for achieving maximum packing and closed textured surface.

The above two will automatically result in the lowest water demand ensuring optimum cement content and thus lowest reactivity [30].

At this stage, as already stated the grading of the aggregate is achieved by the combined all-in aggregate grading in a few codes like DIN [28] and BIS latest norms [29]. However, the ACI and BS look at the grading of coarse and fine aggregate separately and mixing them in an appropriate proportion based on the type of finer material used (fineness modulus of sand as in ACI and particles below 600 microns in the latest BS specification) [30].

Combined all-in aggregate grading used in the present investigation:

From the above discussion, it is obvious that combined all-in grading of aggregates plays a very crucial role in determining

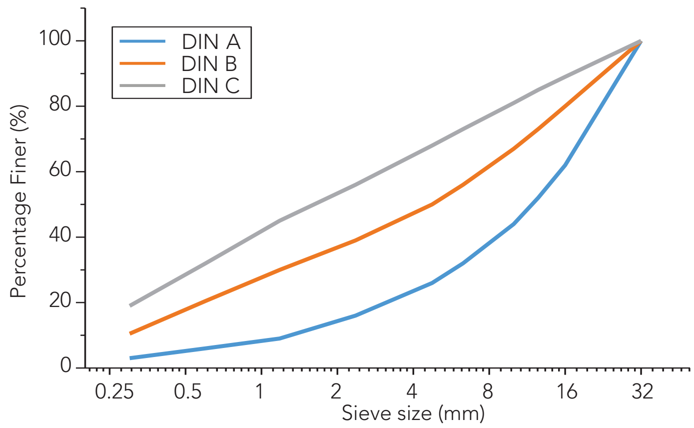

Figure 1: Combined grading curves as per DIN standards [28]

the mechanical as well as durability performance of the concrete to be produced. The sole aim of combined grading is to optimize multiple percent of the aggregate to be used for concrete production in order to get a quality packing of the constituents. Combined grading done as per DIN standards is shown in Figure 1. Since in the case of SCC high workability is desired, the required area in focus is between the curves DIN B and DIN C [32]. The following equation described by Shakhmenko and Birsh [33] can be solved to get combined grading:

$$G \times P = I$$

$$\begin{vmatrix} G_{11} & G_{12} & \dots & G_{1N} \\ G_{21} & G_{22} & \dots & G_{2N} \\ \dots & \dots & \dots & \dots \\ G_{M1} & G_{M2} & \dots & G_{MN} \end{vmatrix} \times \begin{vmatrix} P_1 \\ P_2 \\ \dots \\ P_3 \end{vmatrix} = \begin{vmatrix} I_1 \\ I_2 \\ \dots \\ I_3 \end{vmatrix}$$

Where G = matrix of coefficient consists of grading of aggregates and G_{ij} refers to percent passing of j^{th} aggregate through i^{th} sieve

P = matrix of coefficient consists of unknown percentage of aggregates and P_i refers to percent of j^{th} aggregate to be used for combined grading

I = matrix of coefficient consists of known ideal grading obtained from DIN curve and I_i refers to percent passing as per ideal grading

N = no. of different sizes of aggregate available

M = no of sieves used in the study

Further optimized aggregate combination can be found out by solving the following equation:

$P = G^{-1} \times I$

Subject to constraints

$0 \le P_{ij} \le 1$

3. EXPERIMENTAL INVESTIGATIONS

3.1 Materials and Methods

3.1.1 *Materials*

OPC 53 grade cement meeting the requirements of IS 269 [34] is used in the investigation. Apart from that, CFA, GGBS, and MK were used as SCMs. The physical characteristics of all these cementitious materials are shown in Table 1. NFA is collected from the bed of the locally available Mahanadi river. The individual grading of NFA confirms it to be in Zone-2 as per IS: 383 (2016) [29]. Coarse recycled aggregate (CRA) having a maximum particle size of 20 mm and 10mm, collected from a recycled plant operated by IL&FS in Delhi, were used as a complete replacement with natural coarse aggregates (NCA). In particular, the crushed concrete was carefully chosen and collected from the building and bridge site followed by grinding through horizontal and vertical shaft impactors at multiple levels to get a very good quality of CRA with the least adhered mortar content. Table 2 shows that the RA properties are well below the limits defined in IS 383 [29] and IS 456 [35] and that they can be

Table 1: Properties of cementitious materials

PROPERTY STUDIED	COLOUR	BULK DENSITY (kg/m^3)	MOISTURE (%)	SPECIFIC GRAVITY	SPECIFIC SURFACE AREA (m^2/kg)
OPC	Grey	1135	<0.1	3.14	324
GGBS	Off white	1200	<0.1	3.1	430
CFA	Greyish white	995	<0.1	2.2	350
MK	Off white powder	356	0.21	2.59	15000

Table 2: Properties of CRA and NFA used in the study

PROPERTIES	SPECIFIC GRAVITY	WATER ABSORPTION	ZONE	AGGREGATE IMPACT VALUE (RA)	AGGREGATE CRUSHING VALUE (RA)	ATTACHED MORTAR CONTENT
20 mm CRA	2.33	3.06%	-	18%	20%	13%
10 mm CRA	2.31	5.50%	-			
Natural fine aggregate (NFA)	2.63	0.60%	2		-	
Indian Standard Recommendation	-	< 10% [IS: 456 (2000)]	2/3-	< 30% [IS: 383 (2016)]	< 30% [IS: 383 (2016)]	-

used for structural concrete production. The quantity of adhered mortar was also experimentally calculated, to be only 13%, using the thermal method in accordance with the technique suggested by de Juan and Gutiérrez [36]. According to the SCC criterion, poly-carboxylic ether based super plasticizer (SP) was used to fulfill the EFNARC [37] guidelines, and viscosity modifying agent (VMA) was to maintain the cohesiveness of the mix.

3.1.2 *Individual grading of aggregates*

Individual grading of 20 mm CRA, 10 mm CRA, and NFA are represented in Figure 2, Figure 3, and Figure 4 respectively. It

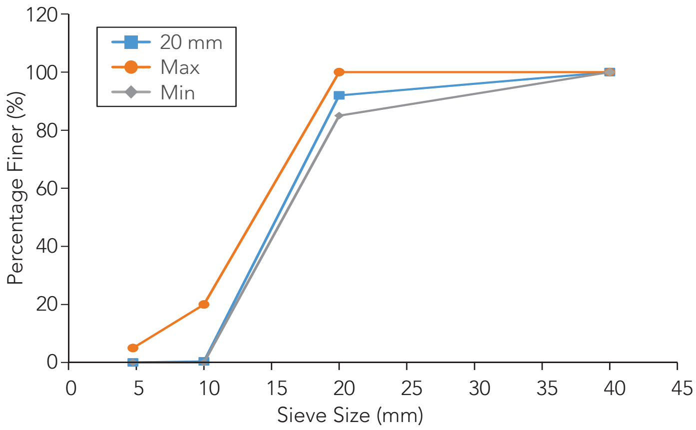

Figure 2: Individual grading of 20 mm aggregate

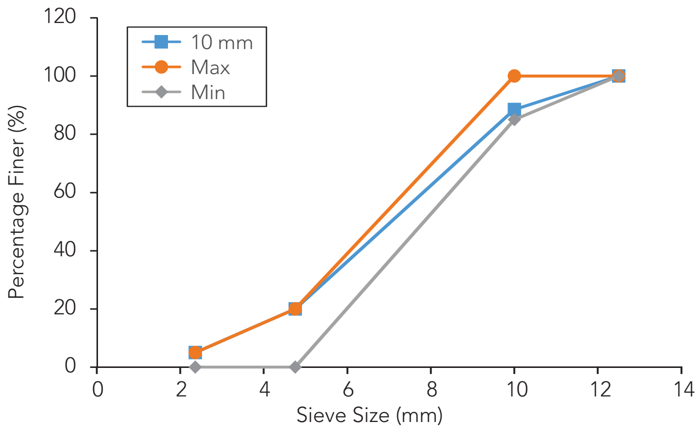

Figure 3: Individual grading of 10 mm aggregate

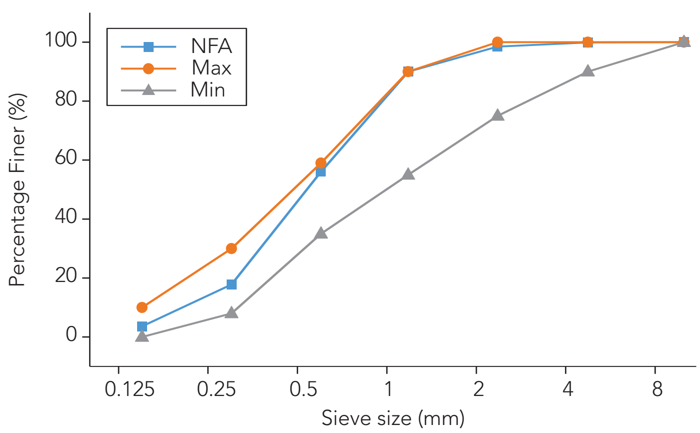

Figure 4: Individual grading of natural fine aggregate (NFA)

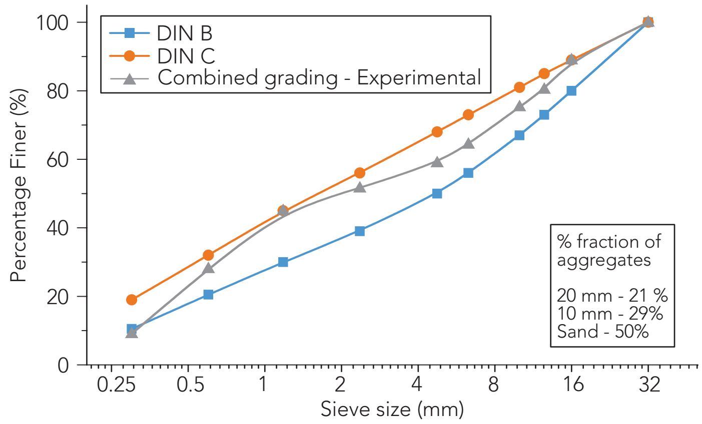

Figure 5: Combined grading of aggregates as per DIN Standard

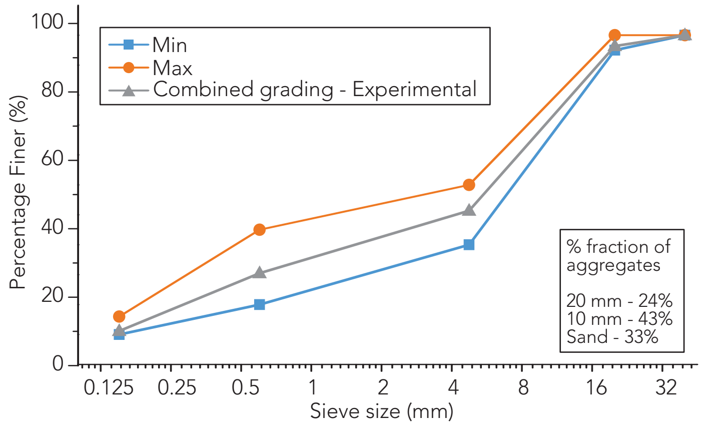

Figure 6: Combined grading of aggregates as per IS: 383 (2016)

can be seen from the Figures that individual grading of 20 mm and 10 mm is within the limit suggested as per IS: 383 (2016) [29]. The grading of NFA confirms it to be under Zone -2.

However, while combining all these individual grading curves with the all-in aggregate grading curves of DIN and BIS standards, the percentage fraction of aggregates obtained was observed to be 21%, 29%, and 50% with DIN, 24%, 43% and 33% with BIS for 20 mm,10 mm, and NFA respectively (Figure 5 and Figure 6).

3.2 Mix Design

There is no well-defined mix design technique specified for SCC containing RA. The idea of all the pozzolanic substance blend mix designs used in the study is drawn out of the previous research reports, and the mixes have been designed accordingly. As per EFNARC [37] guidance, trials were carried out and tested for the new properties after obtaining the proportions of the blend, then further casting of specimens was performed. The classification of the blends for the mix is based on the substitution of cement with the SCMs used in the investigation, for example SM 15 shows that SCC with

Table 3: Mix proportions of RA based SCC at different levels of SCMs following combined grading as per DIN standard

MIX ID	CONTROL	SS 30	SS 50	SS 70	SF 30	SF 50	SF 70	SM 7.5	SM 15
TCM (kg/m^3)	550	550	550	550	550	550	550	550	550
Cement (kg/m^3)	550	385	275	165	385	275	165	509	468
GGBS (kg/m^3)	0	165	275	385	0	0	0	0	0
CFA (kg/m^3)	0	0	0	0	165	275	385	0	0
MK (kg/m^3)	0	0	0	0	0	0	0	41	83
20 mm (kg/m^3)	313	310	308	307	304	297	291	312	310
10 mm (kg/m^3)	428	425	422	419	416	407	398	427	425
Sand (kg/m^3)	841	834	829	824	816	789	783	838	834
Water (kg/m^3)	165	165	165	165	165	165	165	165	165
SP (kg/m^3)	3.3	6.0	6.5	7.0	6.6	6.05	4.4	4.4	6.05
VMA (kg/m^3)	0.28	1.1	1.1	1.1	1.38	1.1	1.1	0.55	0.28

100% of RA has a 15 percent substitution of OPC with MK. Similarly, SF30 shows the SCC contains 30% replacement of OPC with CFA. The control mix comprises 100% RA and OPC as the only binding material. For SCCs with GGBS, and CFA the mixes were designed with 30, 50, and 70 percent GGBS substitutes based on the technique previously suggested by Dinakar *et al.* [38-39]. Also, to achieve high strength SCC, two mixes of 7.5 and 15 percent substitutes of MK with the cement content were produced as per the mix design given by Dinakar and Manu [40]. For all the above mixes, combined gradation is done in two different ways - one with the gradation according to DIN standards and the other with the BIS code's combined gradation. The proportion of the concrete mixes based on combined grading as per DIN standard and BIS are represented in Table 3 and Table 4 respectively.

4. EXPERIMENTAL PROCEDURE

In this analysis, slump flow, V-funnel, T500, and L-box tests investigated the properties of fresh SCCs, as shown in Figure 7, to ensure SCC's flowability, viscosity, passing, and filling ability, respectively. All of the above studies were performed according to EFNARC [37] guidelines. The compressive strength was determined as per Indian standard IS 516 [41]. The compressive strength test was performed on the 3000 kN capacity Controls Advantest-9 servo-hydraulic unit.

Table 4: Mix proportions of RA based SCC at different levels of SCMs following combined grading as per Bureau of Indian Standards

MIX ID	CONTROL	SS 30	SS 50	SS 70	SF 30	SF 50	SF 70	SM 7.5	SM 15
TCM (kg/m^3)	550	550	550	550	550	550	550	550	550
Cement (kg/m^3)	550	385	275	165	385	275	165	509	468
GGBS (kg/m^3)	0	165	275	385	0	0	0	0	0
CFA (kg/m^3)	0	0	0	0	165	275	385	0	0
MK (kg/m^3)	0	0	0	0	0	0	0	41	83
20 mm (kg/m^3)	358	355	352	350	347	340	333	356	355
10 mm (kg/m^3)	635	630	626	622	616	604	591	633	630
Sand (kg/m^3)	555	550	547	544	539	528	516	553	550
Water (kg/m^3)	165	165	165	165	165	165	165	165	165
SP (kg/m^3)	3.47	6.7	7.2	7.6	9.15	8.12	5.37	5.37	8.2
VMA (kg/m^3)	0.28	1.1	1.1	1.1	1.38	1.1	1.1	0.55	0.28

(a) (b) (c)

Figure 7: Experimental setup for (a) Slump flow, (b) V-funnel, and (c) L-Box test

4.1 Results and discussion

4.1.1 *Fresh Properties*

Table 5 shows the fresh properties obtained for all SCC mixes. The primary motivation was to make RA-based SCCs with slump flow values in the 700-800 mm range, which was accomplished by adjusting the dosages of SP and VMA accordingly. It can be observed from Figure 8 that in all the cases requirement of SP is quite higher in the case of RAC made when the grading is done as per BIS code. Also, it can be observed that although having a higher specific area, reported in Table 1, the inclusion of CFA into the concrete mix increases the workability. This is due to its spherical shape that causes a ball-bearing effect in the mix and requires less SP to get equal workability [42]. Whereas GGBS and MK's inclusion increases the SP requirement because of its asymmetrical shape [43] and enormous surface area as mentioned in Table 1.

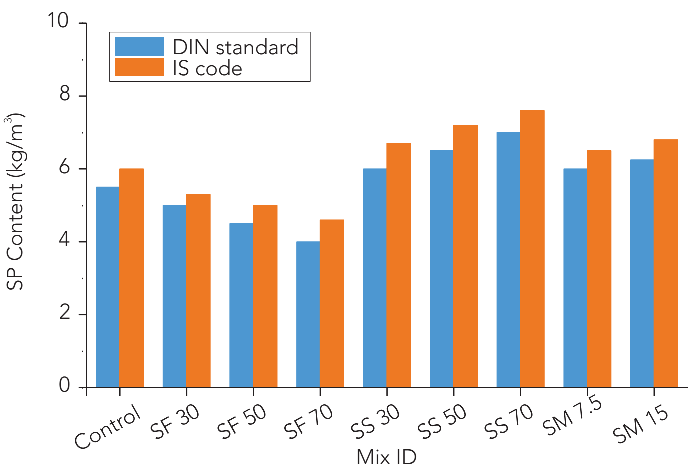

Figure 8: SP requirement for different Mix ID

The slump flow findings show that, as per EFNARC [37], all SCC mixes have their place in the SF2 class group, and a similar pattern was also observed by Grdic *et al.* [19]. Along with the V-funnel test, the viscosity performance of SCC was measured by T500 flow time. As the substitution ratio of integrated mineral admixture increases, the T500 flow time increases, and these were in the range of 4-7 secs. This arises from the fact that the paste content that binds the aggregate and enhances cohesion in the short term would be more the surface area, and the concrete mix is easily dispersed. The time values of the V-funnel of all SCC mixes were in the 12 to 22 sec range.

As a consequence of the above factors, the V-funnel time also rises with the rise in the substitution ratio of various SCMs used in this investigation. As per EFNARC [37], all SCC mixes fall into the VS2/VF2 viscosity class. In order to assess the passing capacity of SCC mixes, the L-box test was conducted, and it was found during the test that there was no tendency to block. Also, all concrete mixes have a passing potential in class PA2 with ratios greater than 0.80. Grdic *et al.* [19] reported a similar outcome. The fresh properties of SCCs, as reported in Table 5, shows that all the concretes that were developed with aggregate gradings of DIN and BIS have exhibited similar performance.

Table 5: Fresh properties of the concrete

MIX ID		CONTROL	SF 50	SF 70	SS 30	SS 50	SS 70	SM 7.5	SM 15
Slump flow (mm)	DIN Standard	760	730	730	730	750	770	720	720
	Indian Standard	750	735	725	730	750	760	720	710
T_{500} (Sec)		5.2	4.8	4.8	5.8	6.3	6.8	4.8	4.3
V-funnel (Sec)		12	18	19	18	19	22	13	15
L-box ratio (H2/H1)		0.95	0.86	0.87	0.88	0.9	0.92	0.88	0.9

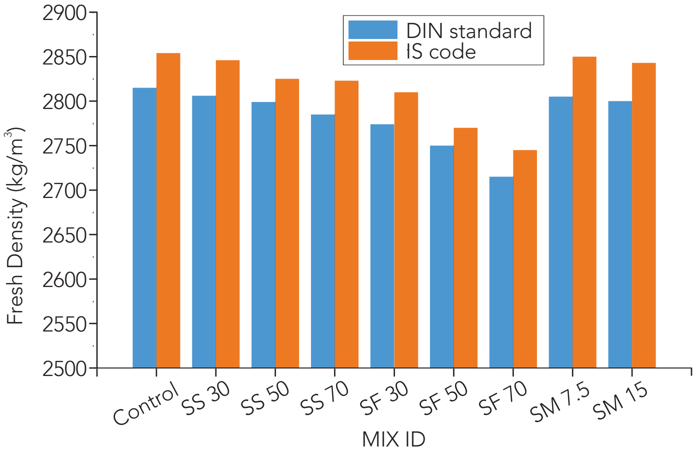

Figure 9: Fresh density of different concrete Mixes

The fresh density for different concrete mixes are shown in Figure 9. It can be observed that following DIN standards provide better particle density than the density of SCC based on BIS code.

4.1.2 *Compressive Strength*

The compressive strength (CS) results illustrated with the incorporation of different level of SCMs at various ages is shown from Figure 10 to Figure15. It was noted that SCC with 100% OPC for up to 7 days exhibited a relatively greater rate of strength benefit than SCC with various SCMs. But SCC mixes of various SCMs exceeded the SCC with only OPC as binder from the 7th day. The impact of CFA on CS of RA-based SCC is shown in Figure 10 and Figure11 Significant CS increase was observed in all SCC mixes having CFA from the 28th day onwards. The possible cause may be a late pozzolanic reaction and slow hydration rate in these mixes, contributing to the delayed development of C-S-H gel, resulting in later strength [44-45]. From 28 days to 56 days, a 30 percent substitution of OPC with CFA demonstrated almost 30 percent of CS benefit. Due to the late formation of hydration materials, i.e., C-S-H gel and calcium hydroxide (CH), as the OPC content is only 30 percent, the CS of mix SF 70 at 56 days was poor. And as the reduction in the presence of CH, the pozzolanic reaction did not occur to the degree possible. Therefore, compared with every other level of CFA substitution, the CS of the SF 70 was inadequate.

For various GGBS replacements, the CS variation is shown in Figure12 and Figure13. The strength increase rate was good for different GGBS substitutes but up to 14 days less than the control mix. But for GGBS substitution ratios of 30 and

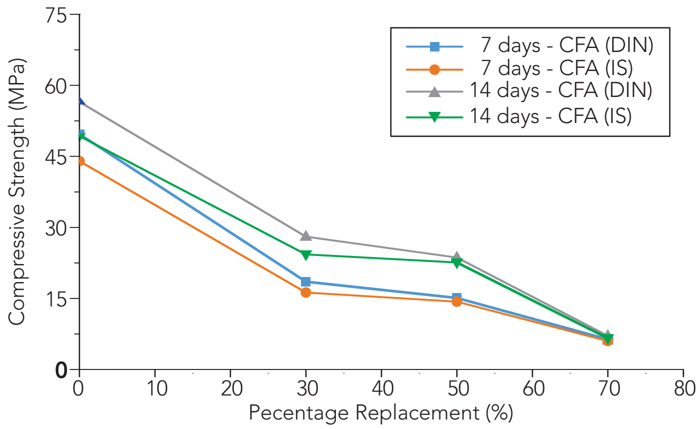

Figure 10: Compressive Strength of CRA based SCC with various replacement of CFA at 7 and 14 days

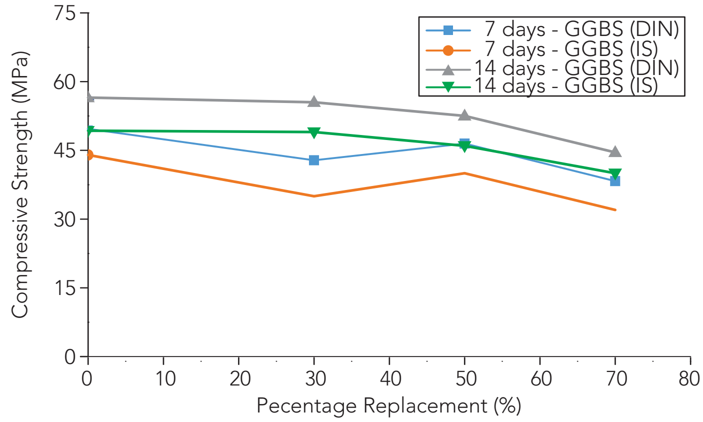

Figure 12: Compressive Strength of CRA based SCC with various replacement of GGBS at 7 and 14 days

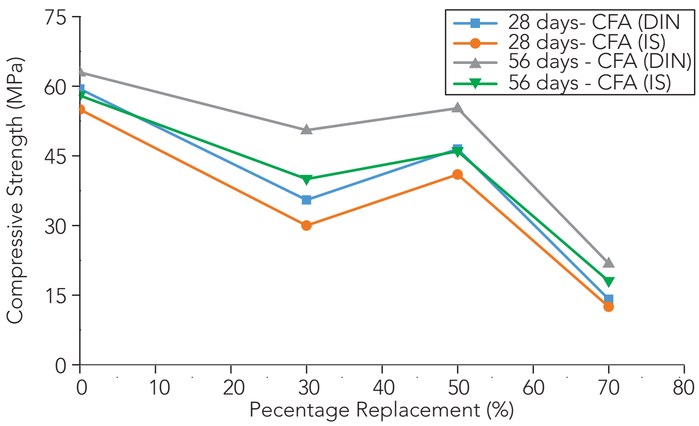

Figure 11: Compressive Strength of CRA based SCC with various replacement of CFA at 28 and 56 days

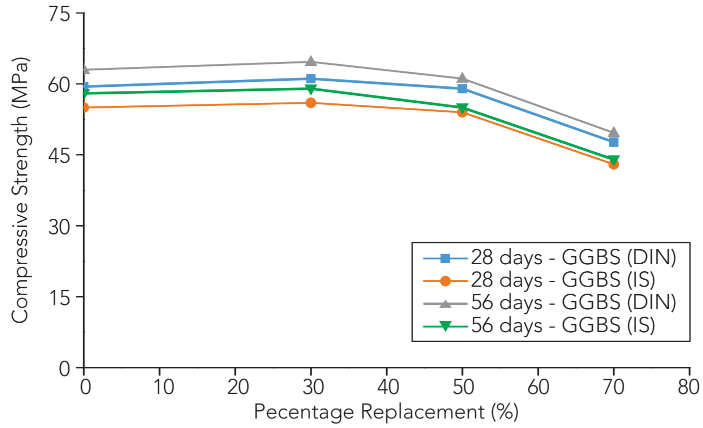

Figure 13: Compressive Strength of CRA based SCC with various replacement of GGBS at 28 and 56 days

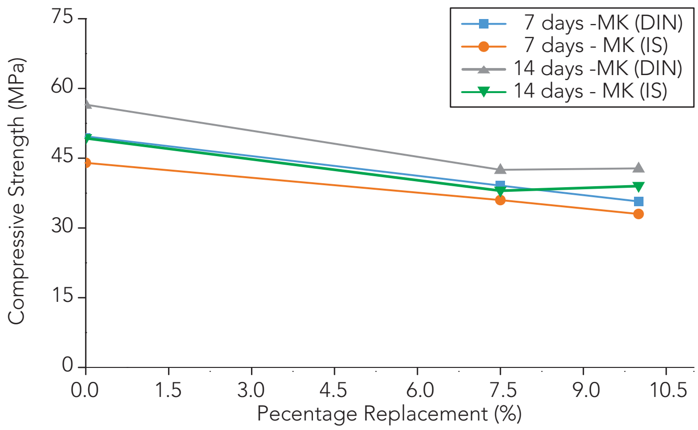

Figure 14: Compressive Strength of CRA based SCC with various replacement of MK at 7 and 14 days

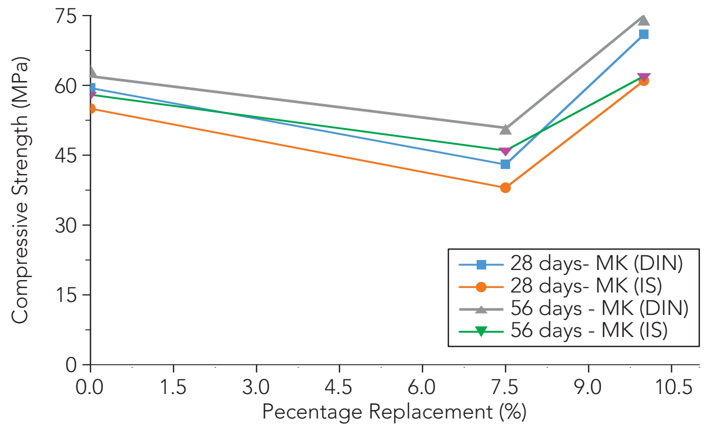

Figure 15: Compressive Strength of CRA based SCC with various replacement of MK at 28 and 56 days

50 percent, CS after 14 days was close to the control mix. It is because of the latent hydraulic property of GGBS, protracted pozzolanic reaction, and delayed hydration that densified the microstructure, giving the power on and after 28 days [38, 46]. Compared to the other two mineral additives, MK is a highly effective pozzolanic substance that imparts more significant advantages. The initial rate of strength gain was poor for SM 7.5 and SM 15 relative to the control combination, but SM 7.5 subsequently showed comparable strength. After 14 days, SM 15 showed remarkable improvement attributed to MK's micro-filling capacity, which contributes to minimize the voids between cement particles and improves the cracks in RA [40]. Thus, due to the intensely active pozzolanic reaction and pore refinement of concrete, the cement paste-RA interface was enhanced. At 28 and 56 days, MK considered that it was more efficient to obtain compressive strength. Kapoor *et al.* [47] has formulated a similar inference. It is evident from the above findings that, when properly constructed, CS in the broad range of 20-75 MPa can be accomplished by judiciously using SCMs and RA in SCCs.

The strength results reveal that SCCs developed with DIN all-in aggregate grading had exhibited higher strengths than those developed with the all-in aggregates grading of BIS. If the all-in aggregate grading specifications of DIN and BIS are taken into consideration (Figure 1 and Figure 6), it can be seen that the permissible range of variation is of the order of 40 percent at some of the sizes in BIS compared to DIN. Based on the experience of the authors, it will be very hard to maintain the workabilities with such a wide discrepancy allowed in the gradings for both coarse and fine aggregates in BIS. This is a problem especially for high strength concretes. Currently, weight batching plants are being adopted and the aggregates batched in weight, the required gradings for the coarse and fine aggregates and also the all-in aggregates can be easily obtained within a very narrow range. As a result, the successive sieve sizes for establishing the grading requirements of coarse aggregates can be chosen nearer. This obviously means that there is an urgent necessity for a relook into this aspect [30].

Further tightening of the grading specifications can be achieved for BIS by prescribing more points between the minimum and maximum particles sizes for grading curves to pass through. The more such points are prescribed the more details can be specified for the gradings [48].

5. CONCLUSIONS

The following findings were taken from the review of the experimental effects of this report:

- The all-in aggregate gradings results of DIN and BIS standards reveal that, BIS exhibits very large variations and needs a closer examination. The large variations allowed in BIS will lead to wide variations in the fresh properties of SCCs. SCCs developed as per DIN standards exhibited better properties both in the fresh as well as in the hardened concrete properties.
- Without showing any signs of segregation, SCC produced using RCA with distinct SCMs such as CFA, GGBS and MK are robust in terms of flowability, passing ability, and high cohesiveness. The criteria to certify them as SCCs as per EFNARC (2002) guidelines have been fulfilled by all SCCs.
- Compared to the inclusion of CFA and GGBS in concrete, the inclusion of MK in concrete increased the mechanical properties of concrete significantly. In addition to this, a concrete blend comprising GGBS with 30 and 50 percent substitution of OPC also shows good mechanical efficiency. As far as the mechanical properties are concerned, the 15% substitution of OPC with MK showed outstanding performance.

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Cite this article: Biswal, U. S., Pasla, D. (2021). "Effect of aggregate grading on the fresh and mechanical performance of recycled aggregate self-compacting concrete", *The Indian Concrete Journal*, Vol. 95, No. 5, pp. 30-40.

AN EXPERIMENTAL STUDY IN DEVELOPING SELF-COMPACTING CONCRETE AS PER IS:10262 (2019) BY UTILISING THE MARGINAL MATERIALS AS FINES

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Abstract

Self-compacting concrete (SCC) is a flowable mix, which can spread and fill the form work completely encapsulating the reinforcement and consolidating on its own self-weight while maintaining the homogeneity.

In the present study an experimental work was carried out to develop M30 grade SCC using IS: 10262 (2019). Five different SCC mixes were developed by utilizing fly-ash and Ground Granulated Blast Slag as filler materials along with particle size less than 125 microns choosing from natural river sand, marble dust, fly-ash, dried ready-mix concrete sludge, and granite sludge as fine materials. The powder content, cement content, and water content of the developed mixes were maintained at 550 kg/m^3, 334 kg/m^3 and 200 lt/m^3 respectively. The maximum size of the coarse aggregates was 20 mm. The developed SCC mixes satisfied the requirements of fresh properties. The morphology of the microstructure of developed SCC mixes was also analyzed through Scanning Electron Microscopy (SEM).

The results indicate that the compressive strength of SCC increases with powder content for the same w/c ratio. Also, the results indicate that the SCC mixes were achieved at powder content above 520 kg/m^3 with w/p ratios of 0.90 to 1.10. The fine materials may be utilized in developing SCC with granite sludge showing better performance as compared to other fines.

Key words: IS: 10262 (2019), SCC, Granite Sludge, Marble Sludge, RMC Sludge, recycled material.

1. INTRODUCTION

Self-Compacting Concrete (SCC) is an advanced type of concrete that can be placed and compacted under its own self-weight with no vibration effort and at the same time cohesive enough to be handled without any segregation or bleeding. It is used to facilitate proper filling and good structural performance of slender sections with congested reinforced structural members [1]. The SCC mix proportion is mainly dependent on the composition and characteristics of its constituents in its fresh state. The fresh properties of SCC will influence the properties in the hardened state [1].

Concrete mix design can be described as the selection of raw materials by optimum proportions to produce concrete with required properties in fresh and hardened states for a particular application. Moreover, the composition of SCC and vibrated concrete (VC) are quite similar. The difference between VC and SCC is in the consistency in the concrete's fresh state and mix ingredients [1]. In general, SCC mix design when compared to VC was described by lower coarse aggregate content, increased paste content, higher powder content, low water-powder ratio, high HRWRA dosages, and the use of VMA in some cases [1]. Over the past decade, various mix-design methods, techniques, and extensive research has been devoted in developing SCC mixture [2]. SCC mix design methods can be divided into five types: viz., compressive strength method; empirical design method; aggregate packing method; method based on statistical model and rheological method [3]. Based on the philosophy of mix design methods, the existing SCC proportioning methods are summarized in Table 1.

Most of the mix proportioning procedures are empirical in nature and necessitate many trials for achieving required fresh characteristics of SCC rather than compressive strength. For the first time Nan-Su [4] developed SCC mix which is based on compressive strength. Later on, other researchers proposed the mix-design of SCC based on compressive strength [5-7]. Lack of uniformity, specific design criterion makes it challenging to compare and evaluate the effectiveness of various design methods in assessing the properties of SCC. However, any mix proportion for SCC must satisfy three criteria in its fresh state viz., filling ability, passing ability, and segregation resistance. So far, the development of SCC mixes was carried out as per,

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Table 1: Existing SCC mix proportion design methods [3]

METHODS	RESEARCHERS	YEAR
Empirical design method	Okamura and Ozawa	1995
	Japan Society of Civil Engineers	1998
	Edamatsa, Sugamata, and Ouchi	2003
	Domone	2009
	Khaleel and Razak	2014
	American Concrete Institute	2007
	Girish. S	2009
Compressive Strength method	Nan-Su, Kung-Chung Hsu, His-Wen Chai	2001
	Ghazi, and Al Jadiri	2010
	Dinakar, Sethy, Sahoo	2013
	Nataraj *et al.*	2016
Aggregate packing method	Hwang, and Tsai	2005
	Petersson, Billberg, and Van	1996
	Su, Hsu, and Chai	2001
	Sedran, and F.de.Larrard	1996
	Shi, and Yang	2005
	Sebaibi, Benzerzour, Sebaibi, and Abriak	2013
	Kanadasan and Razak	2014
Statistical model method	Khayat, Ghezal, and Hadriche	1999
	Ozbay, Oztas, Baykasoglu, Ozbebek	2009
	Bouziani	2013
Rheological method	Saak, Jennings, and Shah	2001
	Bui, Akkaya, and Shah	2002
	Ferrara, Park, and Shah	2007

EFNARC guidelines, ACI method, Nan-Su method, Okamura Method, Re proportioning method, Gettu Method, Girish Method, etc. In India, recently, the Bureau of Indian Standard (BIS) has revised the guidelines for the design and development of concrete mixes and for the first time included the mix design method for SCC.

2. BACKGROUND

In the revised guidelines IS: 10262 (2019) [8] the fines (<125 μm) of about 8% (in fine aggregate) is recommended in proportioning SCC mixes and this particular fines content (8%) is pivotal in determining the fine aggregate content. It is impractical for specific percentage of fines either to be present in the fine aggregate; (or) procure fine aggregate with a specified value of fines (particle size <125 μm); nor assume fine aggregate to have specific fines content irrespective of its gradation characteristics and zonal classification. Even fine aggregates belonging to a particular zone as per IS: 383 (2016) [9] shall consist of fines content (%) in a broad range not a specific value. Also, there are no specific recommendations regarding the possible measure which is to be adopted under such circumstances i.e., when the percentage of fines is more than or less than a specific value. This is evident in the current case, especially when the amount of fines is less than specific value (<8%). To attain the required fines content in fine aggregate, it may be necessary to add fines in addition to existing fines content in the fine aggregate, thereof to calculate fine aggregate content and estimate the coarse aggregate content for a given SCC mix.

Adding fines poses additional challenges. First, they possess smaller particle sizes means the higher specific surface and utilizing them in construction material is tricky. For this reason, marginal materials like marble, granite, and ready-mix concrete (RMC) sludge are often disposed off via landfills and lakebeds. Second, in the case of utilizing them, which fines (type) must be considered, and why?

The present study attempts to develop SCC mixes using IS: 10262 (2019) [8] along with different fine materials (particle size <125 μ) and two different types of fillers. The study primarily focuses on developing SCC mixes as per the latest IS guidelines and exploring the possibilities of utilizing marginal materials as fines when required fines content is not available in the fine aggregate portion.

3. EXPERIMENTAL WORK

3.1 Methodology

In the current study, extensive trials were performed and just over 30 trials of SCC mixes (M30 grade) developed using IS: 10262 (2019) [8] are reported. The design principle is based on compressive strength requirements. The mixes were developed using two different filler materials namely, fly ash and Ground Granulated Blast Slag (GGBS) and different fines (particle size <125 μ) namely, natural river sand, marble dust, fly-ash, RMC sludge, and granite sludge.

3.2 Materials

The list of constituent materials and their corresponding properties are tabulated in Table 2.

All the materials were procured from a single source in sufficient quantity to ensure enough availability of material throughout the experimental program and are stored in airtight containers. The natural coarse aggregate used was crushed granite stone which was angular, and all marginal materials were procured from a nearby marketplace. The maximum size of the aggregates used was 20 mm. Natural river sand confirming

Table 2: Material properties

MATERIALS	SPECIFIC GRAVITY	SPECIFIC SURFACE (M²/KG)	WATER ABSORPTION (%)	REMARKS
Cement	3.14	280	-	OPC-53 grade; (conforming IS:12269 (2013) [10])
Fine aggregate	2.60	-	2.00	Natural river fine aggregates (confirming Zone-II - IS: 383 (2016) [9])
Coarse aggregate	2.60	-	0.90	Crushed angular coarse aggregate passing 20 mm and 12.5mm downsize
GGBS	2.90	425	-	Confirming to IS: 16714 (2018)[11]
Fly-ash	2.00	325	-	Class 'F' type: (confirming IS: 3812 (2013) [12])
Superplasticizer (SP)	1.09	-	-	Polycarboxylic Ether (PCE) based: (confirming to IS: 9103 [13])
RMC Sludge fines	2.14	435	6.50	-
Granite Sludge fines	3.65	365	6.00	-
Natural river sand fines	2.60	375	2.00	-
Marble powder fines	2.56	325	6.80	-
Water	1.00	-	-	Portable water – pH 7.7 (Conforming to IS: 456 (2000) [14])

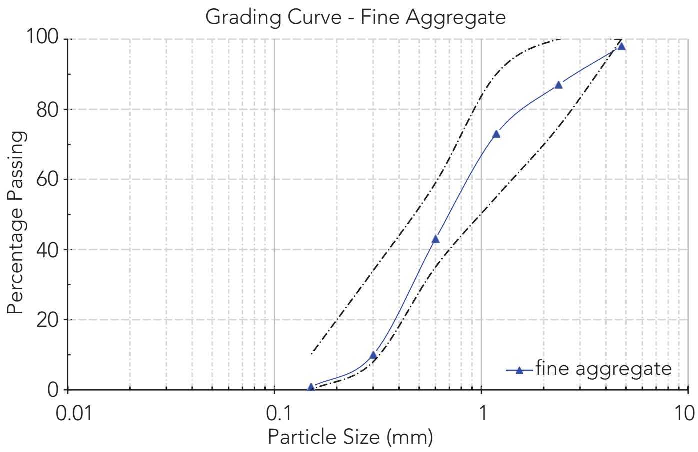


Figure 1: Grading curve of fine aggregate

to zone-II requirements were used as fine aggregate and its gradation curve is shown in Figure 1. Polycarboxylic ether base superplasticizer (SP) used as chemical admixture, which was compatible with the type of the cement used.

3.3 Mix Design

A brief procedure for mix proportioning of SCC as per revised IS guidelines is discussed here. Based on the required grade of concrete to be proportioned, a target strength of SCC is determined (cl. 4.2). Depending on the maximum size of aggregate, air content is determined (cl. 5.2). The water to cement (w/c) ratio is selected for the given grade of cement and compressive strength requirement using the graph of 28-day compressive strength v/s free w/c ratio (Figure 1 of IS: 10262 (2019). Water content is selected from a particular range and further it may be reduced based on the use of SP. Cement content is determined using the w/c ratio and further, the filler may be used to replace cement (generally about 25-50% by weight). The SP content may be determined using the Marsh cone test. A powder content range of 400-600 kg/m^3 is recommended based on slump flow and viscosity of the SCC mix. This powder content comprises cement, filler, and about 10% of fines in Zone-II fine aggregates: considering the particles finer than <125 μm in fine aggregate as powder content. Fines required to be contributed by fine aggregate may be determined by deducting cement and filler content from the total powder content. Fine aggregate content is then calculated using the fines content present in it. Finally, the coarse aggregate content is estimated in volume by deducting the volume of all other constituents like fine aggregate, water, admixture, cement, and filler including air content. The weight of coarse aggregate may be determined using the specific gravity. Before proceeding with the trials, the IS guidelines recommends verifying the water to powder (w/p) ratio by volume and recommends it to be limited to the range of 0.85-1.10.

In the present study, M30 grade SCC was developed using IS: 10262 (2019) [8]. In the first step, the target strength is calculated, based on the equation recommended. The selection of water content was based on the graph of w/c ratio v/s compressive strength (based on the grade of cement) as suggested in IS guidelines. The recommended water content range was 150 - 210 lt/m^3. About 190 lt/m^3 was chosen based on trials and practical field application. The cement content was calculated on basis of the water content chosen and the percentage replacement of filler by weight. After trials, about 40% GGBS by weight of cement was added as filler since replacing 25-50% by weight of cement by filler did not yield the required flow for SCC trials. Marsh cone test was performed to decide on the optimum dosage of SP.

The recommended powder content range as per IS: 10262 (2019) [8] is 400 to 600 kg/m^3. There is no powder content or a specific value; it is a broad range. The powder content constitutes cement, filler, and the fines content present in the fine aggregate. It is required to find the particular powder content to decide on mixes. Though the exact procedure is not stated, the powder content was established through trials in the present study, and the values were verified against the ratio of w/p by volume recommended (0.85 to 1.10) under a note in section E-7.5 of IS guidelines [8]. This value of powder content is important since the fine aggregate content can be established only using the fines content of the fine aggregate. The relation is given by:

Total powder content = cement + filler + 10% fines of zone II fine aggregate.
Fines = Powder – (cement + filler)

The fines present in the fine aggregate was considered to be 8%, to calculate the fine aggregate proportion. The mass of coarse aggregate for the mix is then derived from the volume of coarse aggregate. The volume of coarse aggregate is found by deducting the volume of air content, water, cement, filler, admixture, and fine aggregate from per meter cube of concrete. Calculate the w/p ratio lies between 0.85 and 1.10 as is the recommendation of the IS guidelines.

Discussion:

In this process of mix design, selection of powder content (within the range of 400-600 kg/m^3) and considering 8% fines in the fine aggregate are crucial steps to arrive at mixes. Though, these values help us achieve SCC mixes, how to choose a particular value is unclear. In the present investigation, as already discussed, the powder content was attained through trials.

Also, considering 8% fines in fine aggregates is not practical in all cases. It is again unclear whether to consider the fine aggregate to consist of 8% fines irrespective of actual fines content of the fine aggregate. As discussed in the previous section, this value is very vital to arrive at mixes. Practically, the value of fines even for a Zone-II conforming fine aggregate range between 0 to 10%. Notwithstanding, the fact, range of fines is the same for all four zones of fine aggregate as per IS: 383 (2016) [9].

Some of the observations which were explored for better understanding in the present study are:

- Choosing particular water content from a range of water content (150-210 lt/m^3).
- The remedial measure if fine aggregate does not belong to Zone II and contains fines content other than 8-10%. Without this value fine aggregate content selection is challenging. It is also unclear; this value of 8-10% fines content is an actual value (fines content) or a particular value to be considered irrespective of actual value.
- The range of powder content suggested is 400-600 kg/m^3. One need to explore the characteristics of SCC mixes at about the lower limit of powder content i.e., 400-450 kg/m^3.

3.4 Trial Mixes

The important parameters for achieving SCC mixes are w/c ratio to calculate the cement content; fines content in fine aggregate to determine fine aggregate content; total powder content and w/p ratio by volume. It is true that IS recommended values are achieved, with the SCC mixes so developed. However, given the number of variables and iterations involved it was challenging and cumbersome to achieve mixes with heterogeneous materials. To start with initially, the trials were conducted with lower powder content.

The fine aggregate confirms to Zone II. However, it consisted of about 1.4% fines. The remaining 8% fines was added utilizing various marginal materials having particle size <0.125 mm. Natural river sand fine (NF), marble powder (MP), fly-ash fine (FF), RMC sludge (RS), and granite powders (GS) were utilized as fines of fine aggregate. The IS guidelines has suggested the powder content in the range of 400 to 600 kg/m^3. More than 30 trials were reported maintaining powder content in a particular range. Details of the trials are tabulated in Tables 3, 4, and 5. To decide on the actual powder content to be considered, trials were conducted in three parts. Having powder content of 400 kg/m^3; 400 – 520 kg/m^3 and powder content more than 520 kg/m^3.

The results from Table 3 having lower powder content (about 400 kg/m^3) show that the SCC mixes were not achieved, due to lower cement content (< 250 kg/m^3) and as well as lower powder content. IS: 456 (2000) [14] recommends a minimum cement content of 300 kg/m^3 for structural concrete, it is inclusive of mineral admixture. However, caution has to be exercised for the suitability of mineral admixture to be used in enhancing the engineering properties. In this study, the cement content is exclusively of cementitious materials. Only two mixes mix no. 2 and 12 exhibited flow more than 500 mm; however, mixes were unsuccessful to maintain homogeneity, resulted in bleeding. Also, it can be noted that the w/p ratio for all mixes breached the recommended range of 0.85-1.10. The result has clearly brought out the importance of powder content and recommendation of IS: 10262 (2019) has to be relooked carefully for developing SCC.

SCC trials having powder content 400 to 520 kg/m^3 are reported in Table 4. It can be seen, even with this powder content, mixes exhibited segregation and bleeding. Only one mix (mix no. 17) exhibited flow of more than 500; but failed to maintain homogeneity. It is also interesting to note that, the w/p ratio was achieved in some of the mixes and the value was near to the upper limit of 1.10 in the mix (mix no. 17) which achieved

Table 3: Detail of trial mixes – Powder content (400 kg/m³)

MIX NO.	CEMENT kg/m³	GGBS kg/m³	FA kg/m³	CA kg/m³	FINES kg/m³	POWDER kg/m³	WATER lit/m³	SP %	w/p	SLUMP FLOW mm	RESULT
1	237	79	1050	834	84 (6.6 NF+1.4 RS)	400	180	0.20	1.33	400	Segregation
2	237	79	1050	834	84 (6.6 NF+1.4 RS)	400	190	0.35	1.40	505	Bleeding
3	237	79	1050	834	84 (NF fines)	400	180	0.35	1.33	-	Segregation
4	237	79	1050	834	84 (NF fines)	400	200	0.80	1.48	-	
5	237	79	1050	834	84 (6.6 NF+1.4 RS)	400	180	0.40	1.33	-	
6	237	79	1050	834	84 (6.6 NF+1.4 RS)	400	200	0.60	1.48	-	
7	237	79	1050	834	84 (NF fines)	400	180	0.35	1.33	-	
8	237	79	1050	834	84 (NF fines)	400	220	0.60	1.62	-	
9	237	79	1092	792	84 (NF fines)	400	180	0.20	1.33	-	
10	237	79	1092	792	84 (NF fines)	400	200	0.60	1.48	-	
11	237	79	1092	792	84 (FF)	400	180	0.20	1.36	-	
12	237	79	1092	792	84 (FF)	400	265	0.70	2.00	525	Bleeding

Legends: FA-fine aggregate; CA-coarse aggregate; NF-natural fines; RS- RMC sludge; FF-fly-ash fine; SP-superplasticizer.

Table 4: Detail of trial mixes – Powder content (400 to 520 kg/m³)

MIX NO.	CEMENT kg/m³	GGBS kg/m³	FA kg/m³	CA kg/m³	FINES kg/m³	POWDER kg/m³	WATER lit/m³	SP %	w/p	SLUMP FLOW mm	RESULT
13	255	85	1000	817	80 (GS)	420	180	0.35	1.35	-	segregation
14	255	85	1000	817	80 (GS)	420	195	0.60	1.46	-	
15	384	111	975	351	78 (GS)	500	190	0.60	1.04	-	
16	287	155	975	680	78 (RS)	520	190	0.20	1.05	100	
17	287	155	975	680	78 (RS)	520	300	0.50	1.66	540	bleeding
18	287	155	975	680	78 (GS)	520	190	0.20	1.13	425	No mix
19	287	155	975	680	78 (GS)	520	200	0.90	1.19	500	No mix

Legends: FA-fine aggregate; CA-coarse aggregate; RS- RMC sludge; GS-granite sludge; SP-superplasticizer.

Table 5: Detail of trial mixes – Powder content (>520 kg/m³)

MIX NO.	CEMENT kg/m³	GGBS kg/m³	FA kg/m³	CA kg/m³	FINES kg/m³	POWDER kg/m³	WATER lit/m³	SP %	w/p	SLUMP FLOW mm	RESULT
20	287	155	975	680	78 (RS)	520	190	0.20	1.05	200	No mix
21	287	155	975	680	78 (RS)	520	300	0.50	1.66	-	Segregation
22	287	155	975	680	78 (GS)	520	190	0.20	1.13	620	Bleed
23	287	155	975	680	78 (GS)	520	200	0.90	1.19	-	Segregation
24	384	128	475	709	38 (RS)	550	220	0.50	1.22	-	
25	325	97	963	869	77 (FF)	500	175	0.48	0.91	595	stable mix
26	335	100	963	849	77 (FF)	512	180	0.46	0.92	615	stable mix
27	345	103	950	817	76 (FF)	525	185	0.44	0.92	635	stable mix
28	352	105	963	818	77 (FF)	535	190	0.42	0.92	690	stable mix
29	362	108	938	824	75 (FF)	545	195	0.38	0.93	715	stable mix

Legends: FA-fine aggregate; CA-coarse aggregate; RS- RMC sludge; GS-granite sludge; FF-fly-ash fines; SP-superplasticizer.

Table 6: Detail of mix proportion of SCC mixes

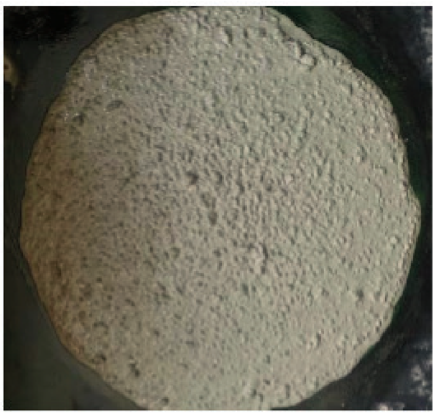
MIX NO.	CEMENT (kg/m³)	GGBS (kg/m³)	FLY-ASH (kg/m³)	FINE (kg/m³)	POWDER (kg/m³)	WATER (lt/m³)	FINE AGGREGATE (kg/m³)	COARSE AGGREGATE (kg/m³)	SP (%)	w/p
SCC1	345	138	-	67 (8% NF)	550	190	837	839	0.40	1.05
SCC2	345	138	-	67 (8% RS)	550	190	837	839	0.60	0.98
SCC3	345	138	-	67 (8% GS)	550	190	837	839	0.60	1.09
SCC4	345	-	138	63 (8% FF)	550	180	835	849	0.40	0.91
SCC5	345	-	138	63 (8% MP)	550	180	835	849	0.36	0.92

Legends: NF-natural fines; RS- RMC sludge; GS-granite sludge; FF-fly-ash fines; MP- Marble powder; SP-superplasticizer.

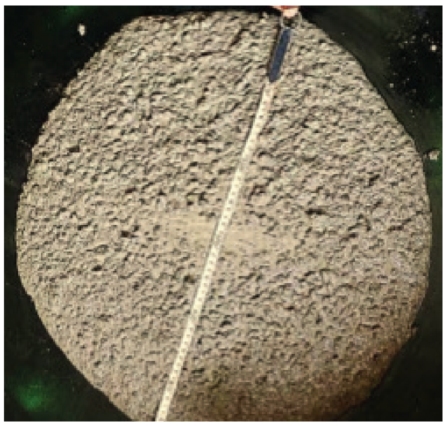
the maximum flow. The results have clearly brought the fact that the recommendation is specific to the type of the ingredients and cannot be generalized.

SCC trial mixes having powder content more than 520 kg/m^3 is reported in Table 5. About 10 different trial mixes are reported, of which 5 mixes exhibited slump flow more than 550 mm, satisfying the fresh property requirements for SCC. The mix nos. 25 to 29 have cement content more than 300 kg/m^3 and powder content around and upwards of 520 kg/m^3. It is also interesting to note that the w/p ratio for these mixes was just above 0.90. These observations indicate that, to achieve stable SCC mixes, the powder content of more than 525 kg/m^3 and w/p ratio of 0.90 to 1.10 is essential. Also, the cement content just above 300 kg/m^3, satisfying the codal requirement for structural concrete. Based on the previous observations, more mixes with different fillers and fines were experimented. The detailed mix proportions are tabulated in Table 6.

As seen from Table 6, it is possible to achieve the SCC mixes, when the powder content is about 550 kg/m^3, cement content is more than 300 kg/m^3 and water content is about 190 lt/m^3 along with different fine materials. For all developed SCC mixes (Figure 2), the fresh properties were ascertained by slump flow,

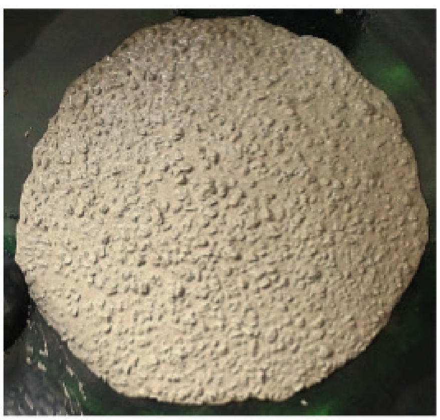


Mix - M1



Mix - M2

Mix - M3



Mix - M4

Mix - M5

Figure 2: Photograph of slump flow of developed SCC

J-ring, and V-funnel tests as per EFNARC guidelines [15]. In order to have a better effect of adsorption of molecules of SP on cement particles, the mixing sequence of the ingredients was changed, and a modified method as proposed by Girish [16,17] was used, wherein the SP and water was taken first before the powder, fine aggregate and coarse aggregate taken in this order. It is also interesting to note that the modified method adopted by Ajay *et al.* [18] to arrive at SCC mixes based on IS: 10262 (2019) [8] also resulted in powder content of more than 520 kg/m^3 and similar w/p ratios. The compressive strength test results were based on standard 150 mm cube tested at different age and precautions were taken to cure underwater at 27 ± 2°C till the age of test as per IS code [19].

4. RESULTS AND DISCUSSION

In case, if w/p ratio is less than 0.85, the theoretical calculations indicate, the fine aggregate content shall be reduced to improve the ratio. If the value is more than 1.10, then the fine aggregate content needs upward revision to maintain the ratio at the permissible level. Such cases result in the revision of theoretical calculations and more iterations. Okumara [1] also advocated w/p ratio and the values indicated (0.90 – 1.10) were quite similar. One can also determine the optimum w/p ratio for zero flow (bp) for paste with the chose proportions of cement and filler. Flow cone test with w/p ratios by volume may be performed with the selected powder content. This will help us to arrive at a particular value of powder content directly, avoiding trials with a range of powder content values, and save a number of iterations and trials.

On an experimental basis, the principle of arriving at optimum w/p ratios proposed by Okamura [1] was adopted to decide on powder content instead of considering directly as indicated in the worked example of IS: 10262 (2019) [8] but still, followed the recommended procedure for SCC mixes. On this basis, about 20 trials were performed which resulted in powder content of about 550 kg/m^3 to establish better flow characteristics. Thus, this value of powder content was adopted, and SCC mixes were developed through the addition of fines (utilizing variety of fines) to the existing fines content in fine aggregate (of 1.4%) to attain required 8% (fines) to calculate fine aggregate content in the mix.

The fresh properties of SCC mixes were evaluated to assess the flowability, passing ability, and segregation resistance of the mixes. The same proportions were then examined for their compressive strength, tensile strength, and flexural strength at 28 days. Both fresh and hardened properties of developed SCC mixes are tabulated in Table 7.

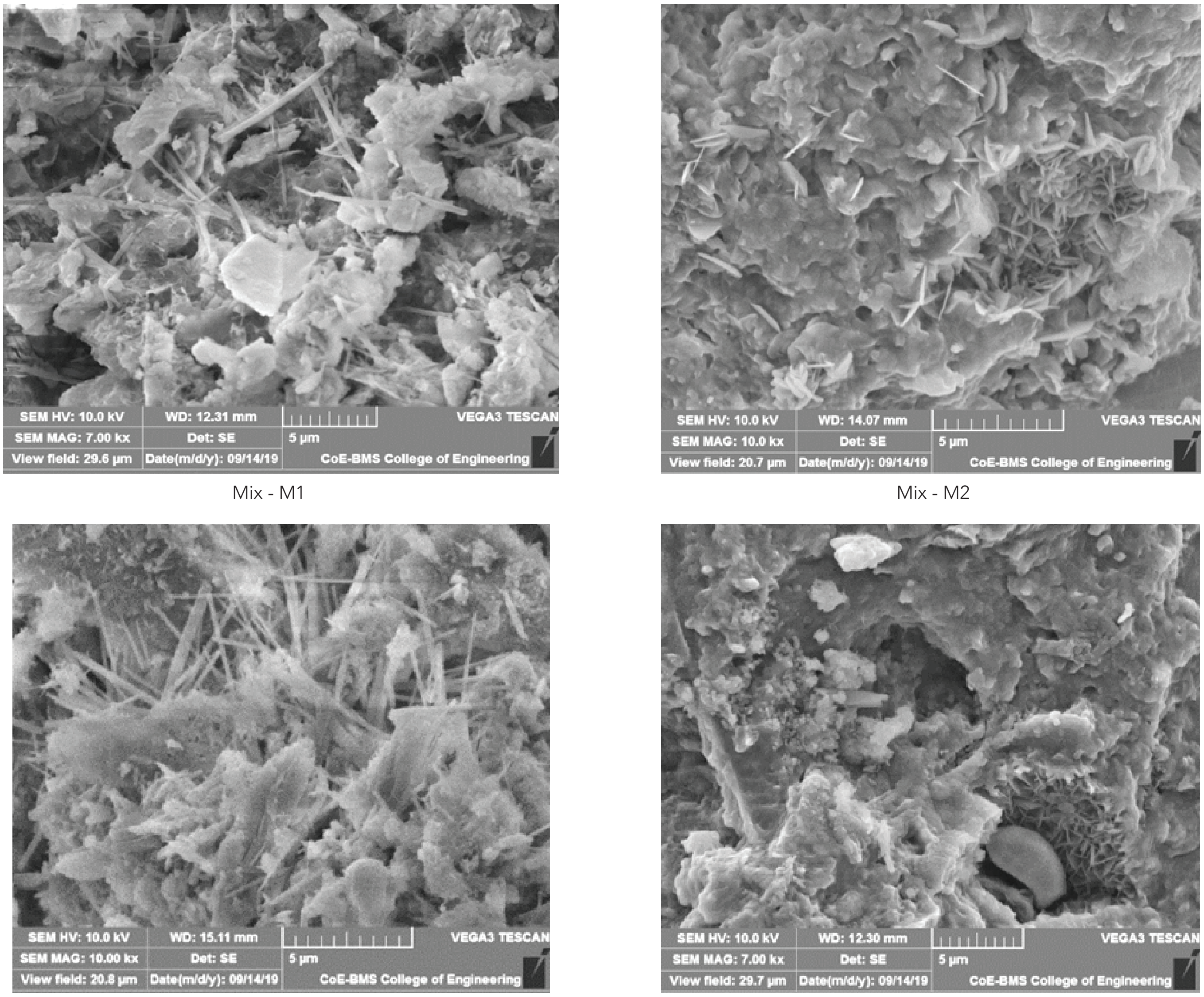
The slump flow values ranged from 590 mm to 630 mm; T50cm ranged from 3.0 to 4.65 sec; J-ring 2.0 mm to 6.6 mm and V-funnel at zero minute ranged between 7.1 and 10.4 sec. All values were within the permissible limits of the EFNARC guidelines [15]. Thus, the SCC mixes were developed using IS: 10262 (2019) [8]. As seen from Table 7, as the w/p ratio increases the slump flow values increases due to a better coating of the paste on the aggregates, resulting in a better lubricating effect and also probably due to better packing. Similarly, T50cm which is the secondary measurement in the slump flow test indicates the viscosity of the mix and V-funnel at 5 minutes which is an indication of segregation resistance, exhibited values less than 3 seconds over V-zero funnel time.

For all mix w/p ratios, a clear trend is available, that compressive strength increased. This increase in strength with respect to powder was probably due to the effective coating of the paste on the aggregates; well-defined cement paste matrix, which may also result in better packing. It is clearly evident that, the powder content, plays an important role in the compressive strength of concrete. In certain instances, but not all, apparent optimality of powder with respect to compressive strength is noted, even though the number of mixes are limited.

Scanning electron microscopy on the tested samples of these mixes was carried out and the images are presented in Figure 3. The analysis was limited to observe the morphology, C_3S formation, and pores. It was noted, the C_3S (alite) deposits were clearly evident in all the samples. The morphology of C_3S is a combination of needle-like formations and amorphous hydrates.

Table 7: Fresh and hardened properties of SCC mixes

MIX NO.	POWDER (kg/m^3)	w/p	SLUMP FLOW (mm)	T50 cm (sec)	J-RING (mm)	V-FUNNEL (sec)		AVG. COMPRESSIVE STRENGTH (MPa)	AVG. SPLIT TENSILE STRENGTH (MPa)	AVG. FLEXURAL STRENGTH (MPa)
						$V_{0\,min}$	V_{5min}			
SCC1	550	1.08	615	3.00	6.6	7.1	10.8	42	3.5	6.8
SCC2	550	1.10	620	3.20	6.3	8.5	11.4	44	3.8	6.2
SCC3	550	1.15	630	3.90	4.0	8.9	11.9	46	3.6	5.9
SCC4	550	0.92	600	4.65	3.0	10.4	12.3	38	3.5	5.8
SCC5	550	0.92	590	3.70	2.0	7.2	10.2	40	3.4	5.5



Mix - M1

Mix - M2

Mix - M3

Mix - M4

Figure 3: SEM Photograph of SCC mixes

No significant differences were observed in the microstructure of all five mixes, and the distribution of C_3S was largely uniform. The distribution of pores was also similar in all the mixes. The sample used in the investigation was a fractured unpolished sample.

5. CONCLUDING REMARKS

The recent revision on concrete mix design guidelines [8] can be effectively used to proportion SCC mixes with certain requirements. The experimental study reveals the powder content plays a major role in achieving SCC mixes. The principle to arrive at optimum w/p ratio, proposed by Okamura could be utilized to find actual powder content while proportioning SCC mixes since the IS specification only provides a wide range of values varying between 400-600 kg/m^3. This can also result in optimizing the number of trials, saving resources. SCC mixes were achieved at powder content above 520 kg/m^3 with w/p ratios of 0.90 – 1.10.

The 8% fines in powder content play a key role in constituting fine aggregate content and further the proportioning of the mix. The fines (< 125 µ) in the fine aggregate may vary from 0 - 10% [Zone II – IS: 383 (2016)]. If the fines present is other than 8% (less or more), the type of course correction and material utilization to fulfill the 8% fines criterion is unclear in the guidelines. However, fines (<125 µ) from marginal materials may effectively be utilized to develop SCC mixes through the procedure recommended in IS: 10262 (2019). The fine materials may be utilized in developing SCC with granite sludge showing better performance as compared to other fines.

ACKNOWLEDGEMENTS

A part of the research work reported in this article secured funding from KSCST (Karnataka State Council for Science and Technology), IISc Campus, Government of Karnataka as a part of the Student Project Program and authors sincerely acknowledge the same. Authors also acknowledge the support of their parent institution RASTA – Center for Road Technology, where the experiments were carried out. Thanks to Sheik Faheem Rizwan, Zeeshan Ahmed and Karthik, former PG students, Infrastructure Construction & Management (ICM), RASTA – Center for Road Technology, Bengaluru for their contribution in performing experiments. Vivian L S, former PG student, ICM, RASTA and Asst. Professor, BMS College of Architecture, Bengaluru for inputs on SEM analysis.

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Cite this article: Ajay, N., Joshi, A. M., Girish, S., Bharadwaj, N. (2021). "An experimental study in developing self-compacting concrete as per IS: 10262 (2019) by utilising the marginal materials as fines", *The Indian Concrete Journal*, Vol. 95, No. 5, pp. 41-50.

SUSTAINABILITY ASSESSMENT OF M25 GRADE RECYCLED AGGREGATE CONCRETE

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Abstract

Construction activities can enhance both economic as well as environmental burden owing to the high cost of building materials, consumption of natural resources and release of emissions to the environment. Conversion of Construction and Demolition (C&D) waste into aggregates that can be used in concrete has emerged as one of the solutions to the above mentioned problems. Through this paper, an attempt is made to assess the sustainability of M25 grade of concrete with different replacement levels of recycled coarse aggregate following a cradle-to-gate life cycle assessment approach. In order to achieve the strength requirement, the mix design parameters were suitably modified with increase in replacement levels of recycled aggregates. Impact assessment was done using CML 2001 baseline method. Results showed that, with optimum usage of coarse recycled aggregates, environmental burden could be reduced.

Keywords: Aggregates, Environment, Impact, Lifecycle, Recycled.

SYMBOLS AND ABBREVIATIONS

C&D : Construction and Demolition
RCA : Recycled Concrete Aggregate
RAC : Recycled Aggregate Concrete
NCA : Natural Coarse Aggregate
LCA : Life Cycle Assessment

1. INTRODUCTION

Concrete remains as the most commonly used construction material for years. The demand for concrete is increasing day by day due to rise in the infrastructure development activities and has resulted in consumption of large quantity of natural resources [1-5]. Building Materials and Technology Promotion Council (BMTPC) under Ministry of Housing & Urban Affairs, Government of India, has reported that there is a shortage of conventional building materials in India as the demand has increased rapidly [6]. Just like many other construction materials, production of concrete also imparts significant impact on environment as it leads to depletion of natural resources and release emissions to environment [1,2]. Out of the different associated processes, manufacturing of cement and extraction of natural aggregates are the major contributors to environmental burden.

Aggregates constitute about 70-80% of concrete [1]. Scarcity of quality aggregates are reported, which might go worse in the coming years [6]. On the other hand, a lot of demolition activities are happening both in the residential and infrastructure segment, which generate huge quantity of construction and demolition (C&D) waste [7,8]. Normally, these are used to for land fill purposes. If unused, these add to solid waste. Hence, there is a need to find alternate use of C&D waste. One of the major applications that the waste concrete from C&D waste finds is to convert that into aggregates, commonly known as recycled concrete aggregates (RCA)[1, 2]. This conversion of waste concrete to RCA has double fold benefit. On one hand, it promotes the reuse of waste concrete, which otherwise become an environmental burden. On the other hand, it reduces extraction of natural aggregates. Hence, this is a stepping stone towards achieving sustainability in concrete construction. However, conversion of C&D waste to RCA is a labour and energy intensive process. Moreover, the mechanical properties of concrete produced from RCA are less compared to normal aggregate concrete [9]. Hence, detailed analysis is required to check whether the use of RCA in concrete production is sustainable or not. This paper focuses on sustainability assessment of M25 grade of concrete prepared with different replacement levels of RCA.

1.1 Conversion of C&D waste to recycled concrete aggregate

The waste building materials and debris generated during construction, repair and demolition of structures are collectively termed as C&D waste [1, 2, 6-8]. Waste concrete obtained from C&D waste could be recycled to derive fine and coarse RCA. The process of recycling consists of a number of activities. Firstly, waste concrete pieces are sorted out from bulk C&D waste. These are subjected to crushing to obtain smaller size,

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typically using an impact crusher or jaw crusher. This is followed by screening to remove very fine particles and sorting to group similar sized fragments [1, 2, 7, 8]. Hence, the entire process of recycling is energy intensive and requires labour. There are mobile C&D waste recycling plants to promote on-site recycling, so that transportation cost is eliminated [1,7].

1.2 Review of the studies on recycled aggregate concrete

When compared with natural aggregates, RCA has higher water absorption. This is due to the presence of adhered mortar content from old concrete which makes the surface of the RCA porous [9, 10]. Due to this adhered mortar, RCA has inferior quality compared to natural aggregates.

The concrete made with RCA replacing natural aggregates is termed as recycled aggregate concrete (RAC) [8]. The properties of RAC depend on the quality of the source of generation of waste concrete and the amount of adhered mortar on the surface of aggregates [9, 19-21]. Studies have been conducted regarding the usage of fine and coarse RCA in concrete and its properties, and are still going on [9, 11-18]. Most of the studies focus on coarse RCA. Table 1 provides summary of literature which have studied the mechanical properties of RCA.

From Table 1, it is understood that concrete shows significant reduction in strength properties when made with 100% RCA even at same water content. In order to compensate for the loss in compressive strength, water cement ratio should be lowered or cement content should be increased or a proper super plasticizer must be used [11-18].

To enhance the quality, various pre-treatment methods are suggested to the prepared RCA for the removal and or for the improvement of adhered mortar. There are physical and chemical methods for the pre-treatment [19-25]. Physical methods such as heating and ball milling effectively remove the adhered mortar and shows better mechanical properties, however, these methods consume large amount of energy. Chemical methods such as acid soaking affect the quality of RCA in view of durability. For strengthening or improving the adhered mortar, methods such as polymer treatment, carbonation, addition of pozzolanic materials etc. are used. Nevertheless, these methods are costly and time consuming.

It is evident from the above paragraphs that either modification in mix design parameters or pre-treatment of RCA could be done for improving the quality of RCA. Both the options have got pros and cons.

Table 1: Summary of literature studying mechanical properties of RAC

REFERENCE	TYPE OF RCA	TESTS PERFORMED	REMARKS
Sahoo *et al.* (2020) [11]	Coarse	CS, FS, STS, ME	• CS reduced for 100% replacement by RCA, showed less reduction in low water cement ratio. • FS, STS values were similar to normal concrete. • ME reduced for 100% replacement by RCA.
Bhashya *et al.* (2020) [12]	Fine	CS, STS	• CS and STS reduced by 20 and 18% respectively for 100% replacement by RCA. • Properties decrease with increase in water cement ratio.
Matias *et al.* (2013) [13]	Coarse	CS, STS	• Addition of RCA reduced strength properties. • Strength reduction could be compensated to some extent by addition of superplasticiser.
Isabel *et al.* (2012) [14]	Coarse	CS, MD	• Properties declined with addition of RCA – 30% for CS and 22% for MD at 100% replacement level. • Reduction in properties increased with increasing replacement level.
Xiao *et al.* (2012) [15]	Coarse	CS, STS, ME	• Showed decreased values of properties with increasing replacement level.
Etxeberria *et al.* (2007) [16]	Coarse	CS	• CS reduced upto 25% for 100% replacement by RCA. • Cement content should be increased to compensate loss in CS
Evangelista *et al.*(2007) [17]	Fine	CS, STS. ME	• Properties decrease with increase in RCA content. • Comparable values obtained at 30% replacement.
Rahal (2007) [18]	Coarse	CS, ME	• Comparable 28 day CS and ME is attained except in higher grades. • Reduction in water cement ratio could compensate for reduction in CS for higher grade.

CS – Compressive strength, STS – Splitting Tensile strength, MD – Modulus of Deformation, ME – Modulus of Elasticity

1.3 Life cycle assessment for sustainability evaluation

There have been impressive efforts put globally for years such that sustainability is considered at par with economy in development. In order to address the increasing pollution, global warming, rapid depletion of natural resources and related consequences, various government and public development agencies focus on 'sustainable development' rather than 'development'[26]. Life Cycle Assessment or Life Cycle Analysis (LCA) has got wide acceptance as a tool for the evaluation and quantification of sustainability of an existing or a new product, method, material, and technology. It is a methodology to support the analysis of environmental burden during the life cycle of a product or technology. It is also used for comparative assessment of two or more products performing the same functions [27, 28]. Many countries have evolved interest on doing LCA of structures and pavements as a decision-making tool [26].

Generally, there are three approaches for doing LCA of a system viz., cradle-to-grave, cradle- to-gate and gate-to-gate approaches. In cradle-to-grave approach, the stages in entire lifecycle of the system are studied whereas in cradle-to-gate approach, the lifecycle extending from start to any intermediate stages are studied. In gate-to-gate approach, one or more intermediate stages in the life cycle are studied [27, 28].

There have been noteworthy studies regarding application of LCA for the assessment of usage of industrial by-products and waste materials for construction. Cradle-to-grave and cradle-to-gate studies have been reported along with comparative assessment. Most of them indicate that the processes of manufacturing of raw materials and transportation require more energy throughout lifecycle stages [5,29-32].

As mentioned in section 1, demand for concrete is increasing rapidly as well as the environmental impact due to extraction and consumption of natural resources is increasing alarmingly. The application of alternatives to ingredients of concrete should be assessed using LCA, to conclude whether these are sustainable options. Hence, there is a need for evaluation of sustainability of cement and aggregate substitutes along with cost, and their properties [29, 30].

This paper presents a cradle-to-gate LCA of concrete made with coarse RCA at various replacement levels. Five mixes are considered, i.e., concrete mix with substitution of natural coarse aggregate (NCA) by RCA at 20, 50, 80 and 100%, along with a control mix. All the mixes were designed as M25 grade. Hence, in order to achieve the objective of attaining a target 28-day compressive strength of 31.6 MPa (for M25) with varying RCA content, the methodology adopted was to vary the cement content and water cement ratio. The details of the same can be found in Section 3. Experiments were conducted to determine the mechanical properties of the concretes.

2. RESEARCH SIGNIFICANCE

It is clear from the above section that there will be huge demand for construction materials in coming years, which could not be met with existing resources. In construction activities, the processes required in material production, transportation and construction phases consume more energy, release emissions and thus create a significant negative environmental impact [5, 31, 32]. To address these issues, strategies to substitute conventional construction materials and material production techniques could be considered. To be precise, use of industrial by-products, recycled materials and techniques such as on-site recycling are great options.

Utilisation of RCA derived from C&D waste, which otherwise create a huge demand for land-filling space, will be a promising option. However, studies indicate that there will be reduction in strength of concrete with increasing replacement level of RCA [9]. To compensate for the reduction in strength, either mix design parameters should be modified or quality improvement of RCA by removal of adhered mortar content should be done. These options consume more materials or more energy. There is a trade off between materials, environment and cost [25]. Hence, application of RCA to concrete should be properly analysed from sustainability point of view in order to assess the feasibility and practicality of the application. Also, comparison of concrete mixes in terms of environmental impact will be worthwhile if they are having equivalent strength.

Hence, in this paper, four RAC mixes at different replacement levels of RCA are compared with control mix (without any RCA replacement) by conducting cradle-to- gate LCA concept (upto production of concrete).

3. EXPERIMENTAL INVESTIGATION

The objective of the experimental investigation was to prepare M25 grade concrete with four replacement levels of RCA viz., 20, 50, 80, and 100% along with control mix (with no RCA). The materials used for the mixes include Portland Slag Cement [conforming to IS: 455 (2015)] [33], crushed stone sand as fine aggregate, NCA, coarse RCA and PCE based chemical admixture. The materials used were tested for their quality following the respective codes [34-36]. Cement, sand and natural coarse aggregates met with required properties and their test results could be found elsewhere [37, 38]. This study focuses on NCA and its replacement by RCA. Hence their test results are discussed in detail here.

Coarse RCA was prepared by crushing old tested concrete specimens from the laboratory. Firstly, the specimens were` reduced to 50 mm size by hammering. Later, these samples were crushed in a laboratory jaw crusher [shown in Figure 1(a)] and sieved. The samples passing through 25 mm sieve and retaining on 10mm sieve was collected [shown in Figure 1(b)].

(a) (b)

Figure 1: (a) Laboratory jaw crusher (b) Prepared RCA

3.1. Properties of natural coarse aggregates and recycled concrete aggregates

The physical properties of both NCA and RCA were determined and the results are presented in Table 2. Specific gravity and water absorption tests of the aggregates were carried out as per IS: 2386 (Part 3). The aggregate crushing value, aggregate impact value and Los Angeles abrasion value were determined according to Indian standards IS: 2386 (Part 4) [33-36].

Table 2 shows that the properties of RCA are inferior compared to that of NCA. As mentioned in section 1.2, this is due to the presence of old mortar adhered to it [9]. Also, higher water absorption was observed for RCA compared to that of NCA because of the same reason [9, 10]. Therefore, appropriate correction was applied while doing the mix design such that the recycled aggregates are brought to saturated surface dry condition.

Figure 2 shows the particle size distribution curves of NCA and RCA. Comparable gradation was obtained for both NCA and RCA. Particles finer than 10 mm were omitted in RCA as finer fractions could affect the quality of concrete.

Though the RCA got inferior properties, they are used as such in this particular study. Another study is going on to assess the influence of various treatment methods to improve the properties of RCA in the same laboratory.

Table 2: Physical properties of NCA and RCA

MATERIAL TEST	NCA	RCA
Specific gravity	2.72	2.56
Water absorption	0.5%	2.2%
Aggregate crushing value	27%	34.12%
Aggregate impact value	27%	35.37%
Los angeles abrasion value	26%	32.32%

3.2 Mix proportioning

Concrete mix design was done as per IS: 10262 (2019) [39] in order to achieve M25 grade concrete for medium workability (Slump value between 50 to 75 mm). The target mean strength of M25 mix is 31.6 N/mm^2. As indicated by the trial data, for given cement content and water cement ratio, compressive strength decreases as the RCA replacement level increases. Hence in order to achieve the target compressive strength corresponding to M25, the total cement content is increased, whereas the water cement ratio is reduced as the replacement level increased. Table 3 gives the details of the mix proportioning.

The admixture dosage was adjusted in order to meet the workability requirement. The raw materials were mixed in a

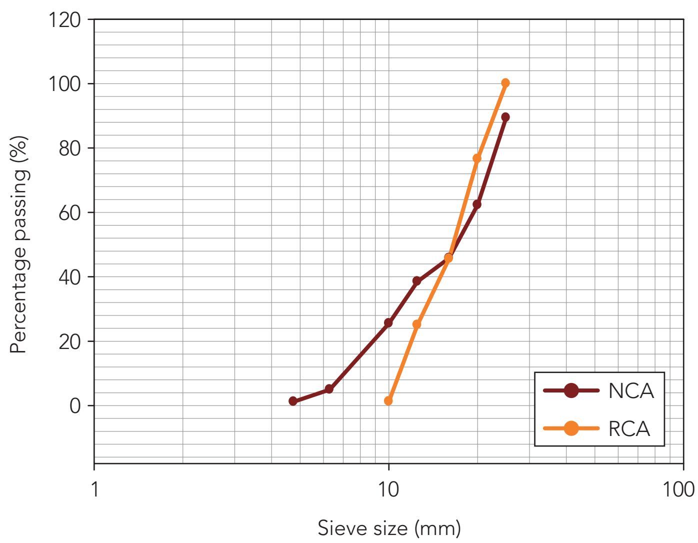


Figure 2: Gradation curve of NCA and RCA

Table 3: Details of mix proportioning

MIX ID	% REPLACEMENT OF RCA	CEMENT CONTENT (kg/m^3)	WATER CEMENT RATIO	WATER CONTENT	FINE AGGREGATE CONTENT (kg/m^3)	NATURAL COARSE AGGREGATE CONTENT (kg/m^3)	RECYCLED COARSE AGGREGATE CONTENT (kg/m^3)	SUPER PLASTICISER DOSAGE
1	0	370	0.42	169	756	1207	-	0.2
2	20	380	0.40	167	756	966	228	0.2
3	50	400	0.40	176	742	591	558	0.2
4	80	400	0.36	165	758	242	913	0.3
5	100	420	0.38	178	734	-	1107	0.3

laboratory pan mixer. Immersed water curing was done for casted concrete specimens.

3.3 Evaluation of mechanical properties of concrete

The mechanical properties evaluated include concrete compressive strength and flexural strength. These tests were conducted as per IS: 516 (1959) [40]. Figure 3 and 4 shows the results of compressive strength and flexural strength of the M25 grade of concrete for different replacement levels of RCA.

All the mixes met the strength requirements of M25 grade concrete and were able to attain comparable properties in terms of flexural strength. Hence, it is evident that in order to attain target compressive strength, as the RCA content increases, it is necessary to increase the cement content and or to decrease the water cement ratio.

4. CRADLE TO GATE LIFE CYCLE ASSESSMENT

A cradle-to-gate LCA considering the stages up to concrete production is conducted for five concrete mixes mentioned above. The materials required for 1 m^3 of concrete was calculated for each case. Figure 5 shows the processes included in the system boundary of concrete production considered for the study.

The processes required for raw material extraction and manufacturing of cement, sand, natural coarse aggregates were considered in the material production phase. Also crushing and sorting of waste concrete to get coarse RCA was also considered for the system boundary for RAC. The materials were transported to the place of mixing. Table 4 shows the transportation distance for each material from source to the laboratory at Kottayam, Kerala. The coarse RCA was prepared from old tested concrete specimens in laboratory and hence transportation was eliminated for the same. LCA results will

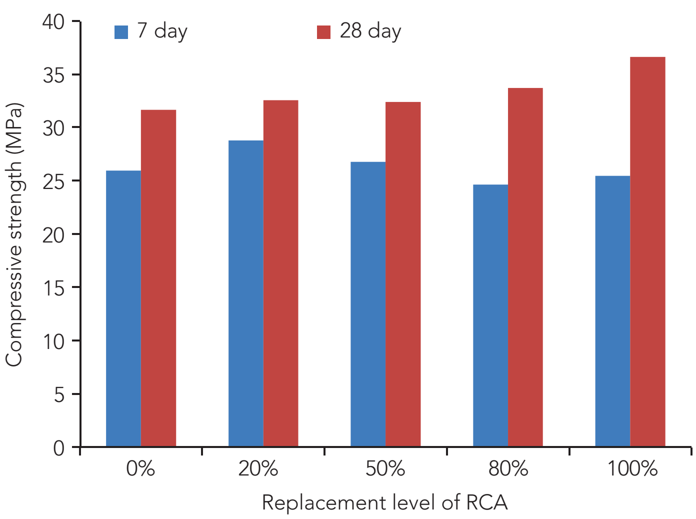


Figure 3: Compressive strength of concrete mixes for different replacement levels of RCA

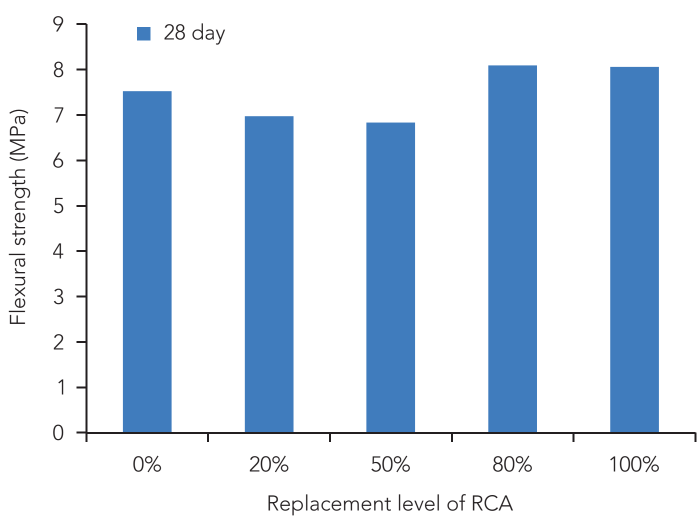


Figure 4: Flexural strength of concrete mixes for different replacement levels of RCA

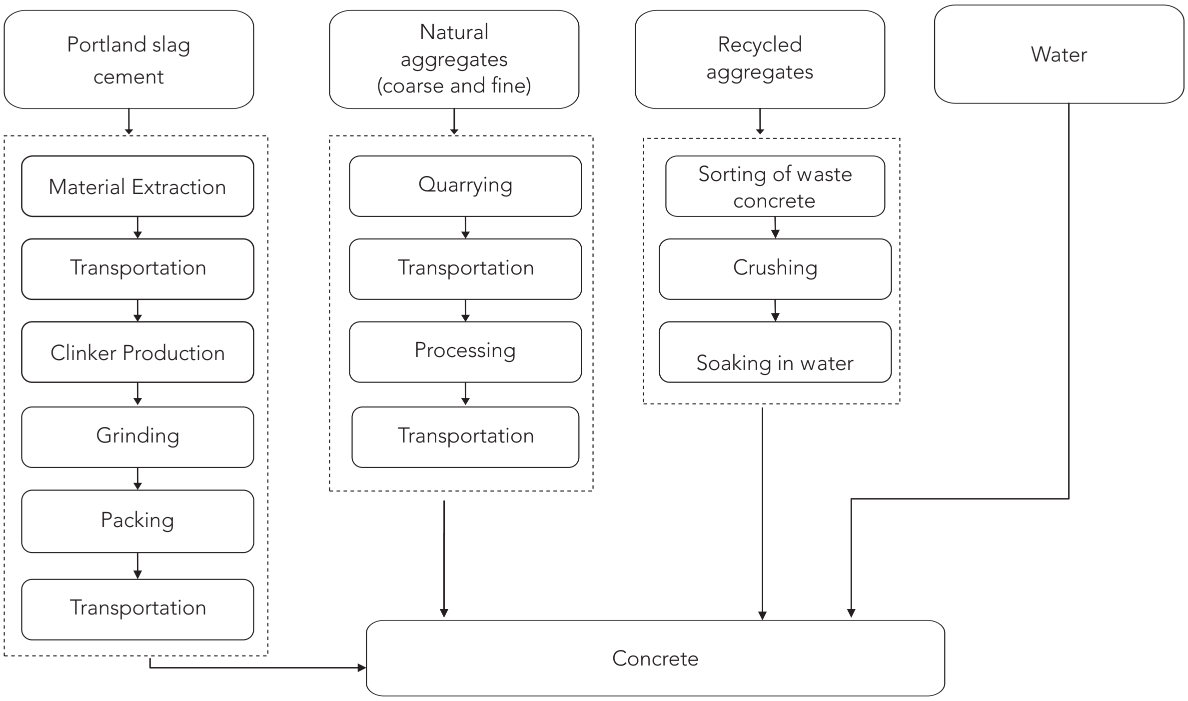


Figure 5: System boundary for concrete production

Table 4: Transportation distance of materials used

MATERIAL	SOURCE	DISTANCE IN km
Portland slag cement	Karikkali, Tamil Nadu	282 km
Natural coarse aggregate	Erumeli, Kerala	33 km
Crushed stone sand	Kayamkulam, Kerala	53.6 km

be influenced by the type of materials used, transportation distance, equipment used in construction etc.

Superplasticiser was not considered among materials, as its amount is negligible compared to other components of concrete. The same approach is reported elsewhere [29]. The details of the processes were collected from manufacturers and Ecoinvent database Version 3 [41]. The inventory analysis and impact assessment were done in OpenLCA software. The environmental burden accumulated for the five concrete mixes were calculated.

The term environmental burden denotes all types of impacts upon environment due to manufacturing a product or a process or a service. In ISO: 14040 (2006), environmental impact is divided into three categories – damage to environment, damage to human health, resource consumption [27,28]. This is because output emissions from a system do not remain in the deposited medium, but gets transferred to others as well [42]. For example, emissions deposited in ground water could be transferred to humans. Hence, most of the life cycle impact assessment methods have end point impact categories such as ecotoxicity, human toxicity, acidification etc.

4.1 Impact Assessment

There are various impact assessment methods like Eco-indicator 99, TRACI, CML 2001 method etc. Each method has got specific group of impact categories. The output flows or emissions derived from a particular system boundary are assigned to each impact category to which it contributes. Then the cumulative load under each category is calculated and assessment is done based on the final impact values. However all the impact assessment methods have got its own pros and cons. Selection of suitable method could be done based on the area of study, goal and scope of the study etc.

Based on the inventory results of the processes listed above, impact assessment of the five concrete mixes considered in the study was done using CML 2001 Baseline method [42]. It is a commonly used impact assessment tool which calculate environmental loading under different impact category indicators like human health, environment and ecology etc. In this study nine impact categories were considered – acidification, ecotoxicity (freshwater, marine and terrestrial), climate change, ozone depletion, resource depletion, eutrophication and human toxicity.

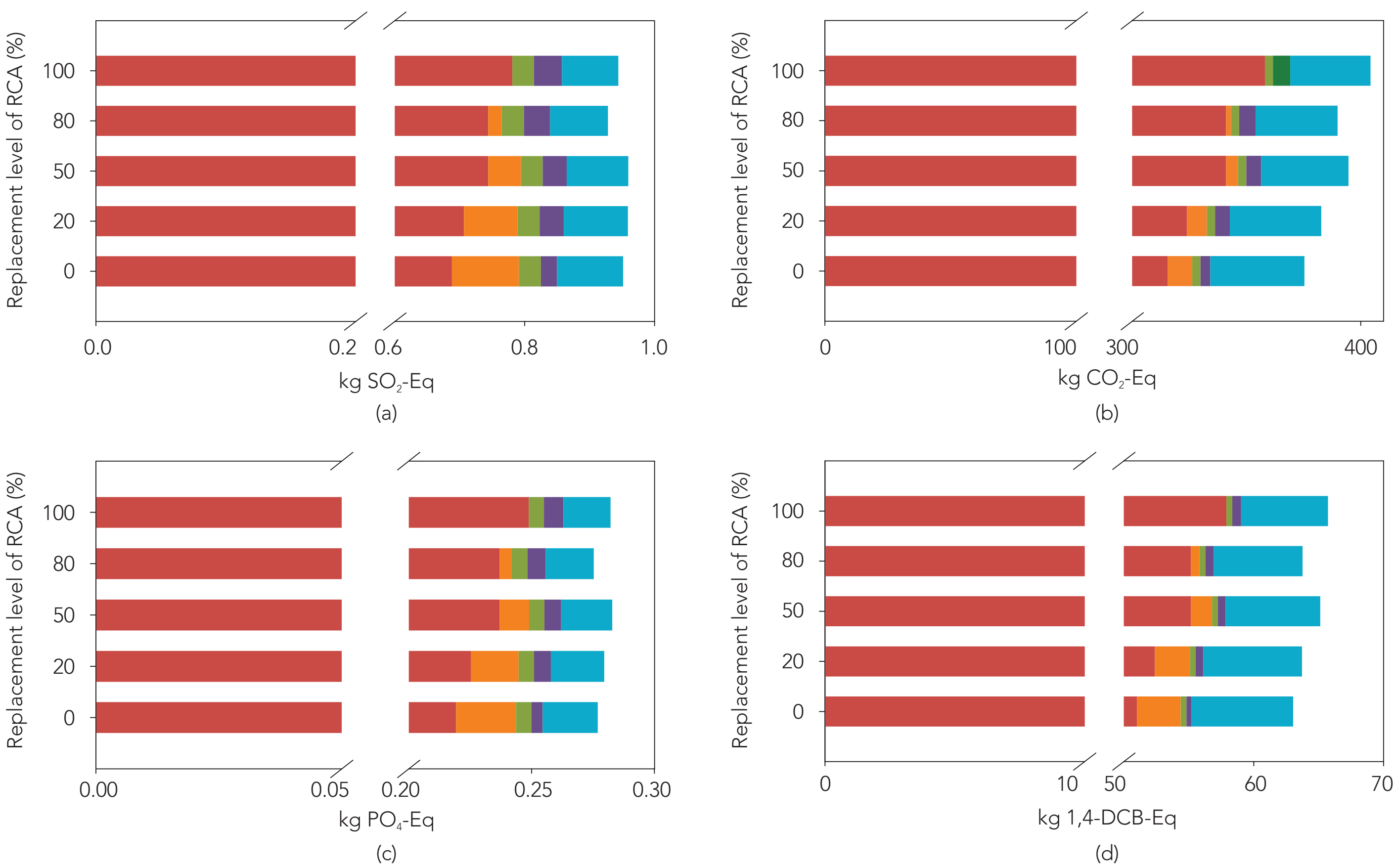
In acidification impact category, the acidification potential of the pollutants emitted is calculated. Major pollutants considered are oxides of sulphur and nitrogen and ammonia. These

Table 5: Impact assessment results

IMPACT CATEGORY	UNIT	MIX 1 (0% RCA)	MIX 2 (20% RCA)	MIX 3 (50% RCA)	MIX 4 (80% RCA)	MIX 5 (100% RCA)
Acidification potential	kg SO_2-Eq	0.952	0.959	0.959	0.928	0.944
Climate change potential	kg CO_2-Eq	375.362	382.734	394.684	389.900	404.285
Eutrophication potential	kg PO_4-Eq	0.277	0.279	0.282	0.275	0.282
Freshwater aquatic ecotoxicity	kg 1,4-DCB-Eq	63.039	63.727	65.117	63.763	65.719
Marine aquatic ecotoxicity	kg 1,4-DCB-Eq	139936.848	140457.831	142001.478	137756.568	141015.359
Terrestrial ecotoxicity	kg 1,4-DCB-Eq	0.739	0.745	0.756	0.737	0.757
Human toxicity	kg 1,4-DCB-Eq	163.343	164.655	167.380	163.355	167.746
Resources depletion	kg antimony-Eq	1.314	1.328	1.341	1.307	1.337
Stratospheric ozone depletion	E-5 kg CFC-11-Eq	1.868	1.891	1.883	1.827	1.851

acidifying pollutants have impacts on soil, water, materials and ecosystem [42]. Ecotoxicity potential considers the emissions that are toxic to aquatic and terrestrial ecosystem. Climate change potential is measured by the change in average temperature, change in seasonal patterns; an example of which is global warming due to release of carbon dioxide and other gases into air. Eutrophication potential is measured by the presence of macronutrients such as nitrogen and phosphorus in excessive levels. This can disturb the terrestrial and aquatic ecosystem [42]. Under human health impact category, toxic substances released into air, water and soil are measured. Ozone depletion potential is measured on the basis of release of chlorofluorocarbons and other equivalent compounds into air. The natural resources that are consumed by the system including energy resources are considered under resource depletion category. The burden due to each concrete mix on each impact category is tabulated in Table 5. All the impact categories are quantified in corresponding units given in the table.

The split up of each impact category results for the five cases of concrete mixes considered are shown in Figure 6. Cement



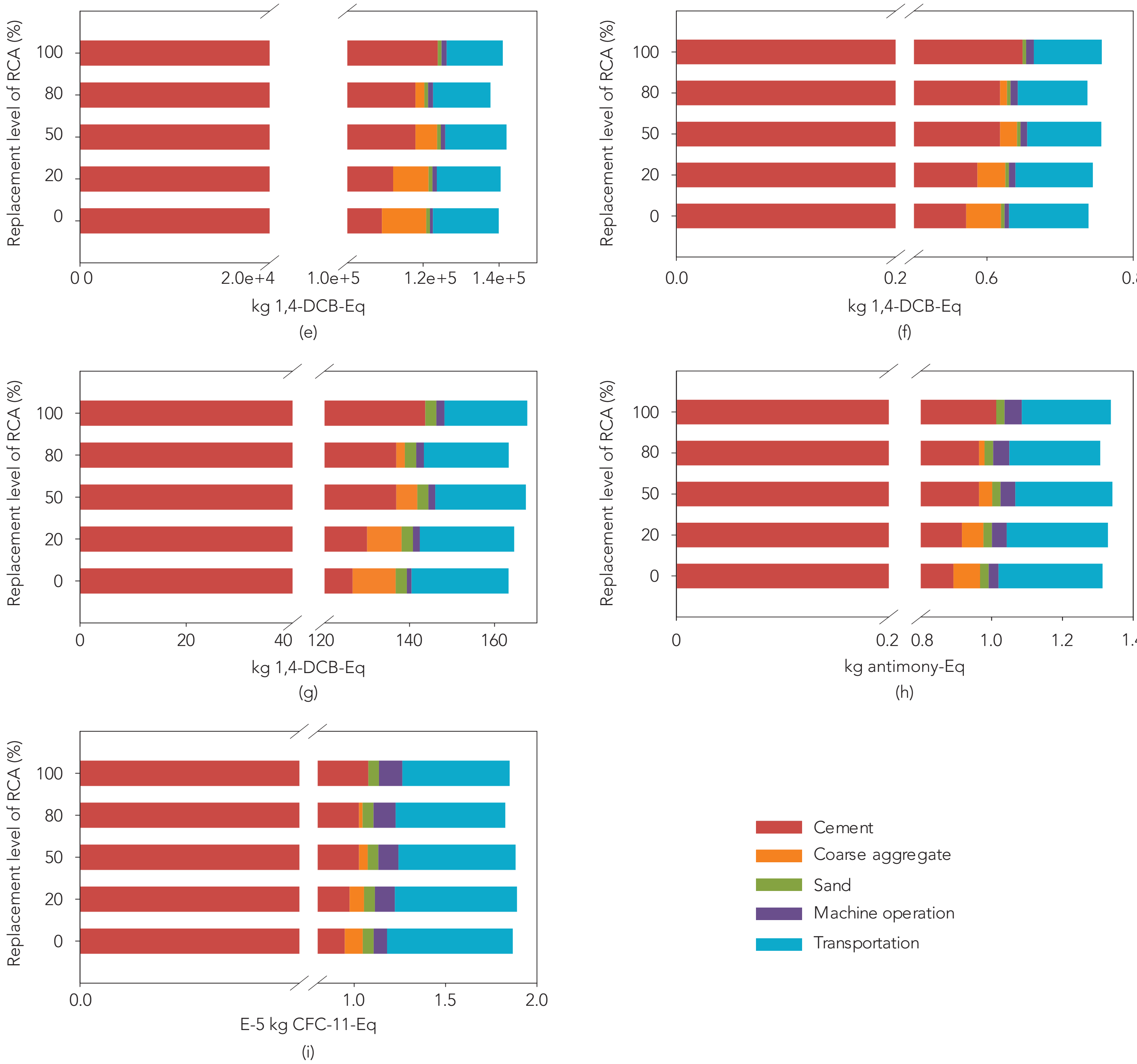


Figure 6: Split up contribution of processes to impact category (a) acidification potential (b) climate change (c) eutrophication potential (d) freshwater aquatic ecotoxicity (e) marine aquatic ecotoxicity (f) terrestrial aquatic ecotoxicity (g) human toxicity (h) resource depletion (i) ozone depletion.

production, coarse aggregate production, sand production, machine operation and transportation are the contributing processes and are depicted in the figure.

Acidification potential increased with RCA content up to 50% replacement; above of which showed reduced impact indicator values. The least value was obtained at 80% RCA content. Both climate change and eutrophication potential increased with increased RCA content, even though slight reduction was observed for the mix with 80% RCA. All the RAC mixes showed increased ecotoxicity potential than control concrete mix except 80% RCA mix which showed reduced impact values for marine and terrestrial ecotoxicity potential. Only the control mix and 80% RCA mix showed comparable impact values for human toxicity potential. All other RAC mixes surpassed the control mix. Similar results were observed with resource depletion potential. In ozone depletion impact category, beyond 50% RCA content, concrete showed reduced impact indicator results. Figure 7 shows the normalised indicator results of all categories considered, with values corresponding to control concrete mix being 100%.

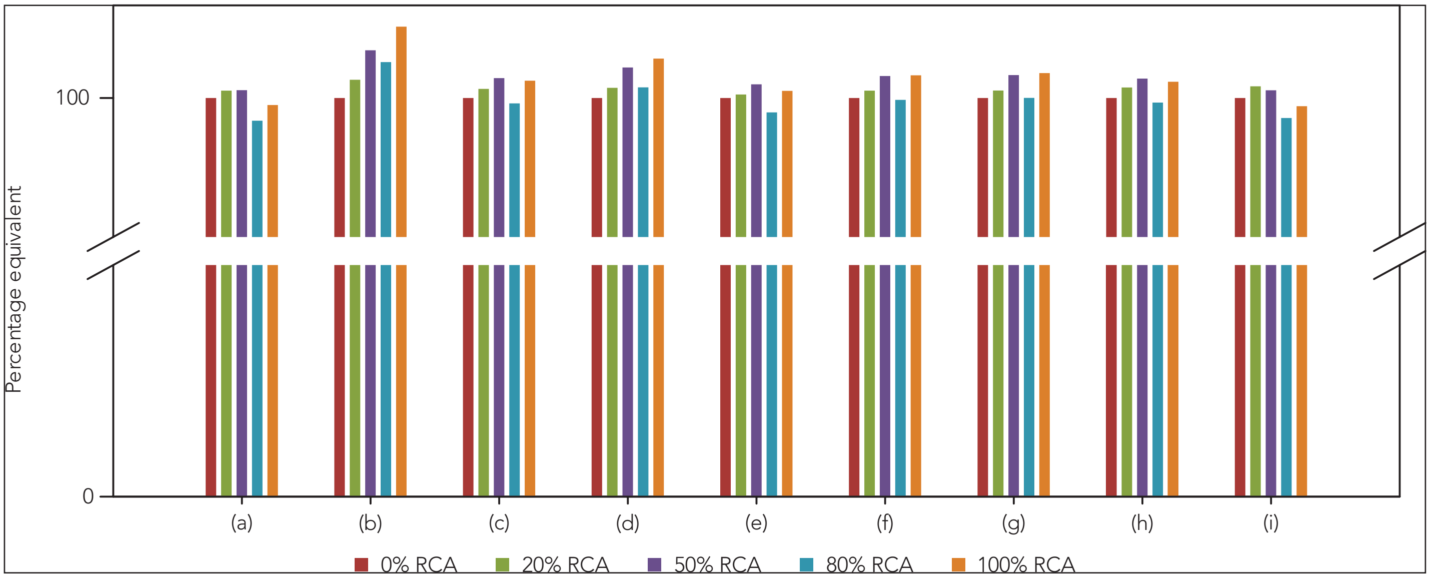


Figure 7: Overall normalised results for impact category (a) acidification potential (b) climate change (c) eutrophication potential (d) freshwater aquatic ecotoxicity (e) marine aquatic ecotoxicity (f) terrestrial aquatic ecotoxicity (g) human toxicity (h) resource depletion (i) ozone depletion

4.2 Summary and interpretation of impact assessment results

The results of the impact assessment are discussed as follows:

- Overall results indicate that of all the processes considered, cement manufacturing is the one with the biggest score of impact category indicator result. It also contributes significantly to emissions responsible for climate change.
- Cement production and natural aggregate production are the top contributors to the environmental impact categories- acidification, ecotoxicity, climate change, eutrophication and human toxicity.
- Along with the manufacturing processes, freight transport is also a noteworthy contributor to the impact categories- ozone depletion and resource depletion.
- It required more cement content with increased RCA content, in order to achieve the target strength. This compromised the reduction in burden due to usage of RCA.
- Use of 80% RCA in concrete reduces the burden on most impact categories except climate change potential. Hence, this replacement level could be considered as an optimum RCA content within the system boundary limits.

5. CONCLUSION

Sustainability of construction could be enhanced by use of alternative construction materials to replace natural materials. In this paper, a comparative cradle to gate assessment is carried out to examine the potential of application of coarse RCA in concrete. Five mixes with 0, 20, 50, 80 and 100% usage of coarse RCA were designed such that all attained the target compressive strength on testing. In order to achieve the same, the cement content was increased and water cement ratio reduced, with increasing content of coarse RCA.

Life cycle assessment was carried out for the production of one cubic meter of the five concrete mixes. Impact assessment of the results was done using CML 2001 Baseline method. Even though the factors such as location of the site, transport distance for freight influence the values, the RAC mixes showed comparable or reduced impact indicator results when compared with control concrete mix. Increased cement content compromises the decrease in impact achieved due to usage of RCA. However, 80% RCA mix could be considered as optimum RCA content, provided similar studies establishes the same.

By analysing the contributions of unit processes to each impact category, it is found that the extraction and processing of natural materials causes the major environmental loads. This necessitates the use of supplementary cementitious materials (SCM), recycled aggregates for sustainable construction.

Transportation of materials to the factory and to the work site releases significant emissions causing ozone depletion and global warming. Hence, distance to source of construction materials should be minimised as possible. As significant reduction in process contributions are observed with 50% and 80% RCA, quality improvement methods must be optimized to enhance more usage of RCA in concrete.

ACKNOWLEDGEMENTS

The authors are thankful to Transportation Research Centre, Trivandrum, Kerala, India for their partial financial assistance. The database providers Ecoinvent and OpenLCA Nexus are also greatly acknowledged.

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Cite this article: Thomas, T. S., Sankaran, V., Jisha, K. V. and Dhanya, B. S. (2021). "Sustainability assessment of M25 grade recycled aggregate concrete", *The Indian Concrete Journal*, Vol. 95, No. 5, pp. 51-62.

Postal Registration number : THC/125/2018-2020 | RNI Number : 13986/57 | Total pages 64
Published and posted on 1st of every month. Posted at Patrika Channel Sorting Office, Mumbai 400 001