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VALORIZATION OF ANNABA STEEL COMPLEX BLAST FURNACE SLAG IN CONCRETE PRODUCTION: A REVEW

Dr. Djamel Beggas*

Department of Architecture, Faculty of Engineering, Al-Baha University, Saudi Arabia.

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***Corresponding Author**
Dr. Djamel Beggas
Department of Architecture, Faculty of Engineering, Al-Baha University, Saudi Arabia.

ABSTRACT

Concrete is a fundamental construction material employed worldwide. Aggregates, along with cement and water, constitute the primary constituents of concrete, accounting for between 55% and 80% of its volume. These aggregates are either extracted from natural deposits or crushed from larger rocks. Aggregate reserves are being rapidly depleted as a result of the continued growth of the global construction industry, which is leading to significant annual increases in the consumption of natural aggregates. Such a high use of natural aggregates represents a serious environmental risk. For this reason, investigating the potential of using waste materials and industrial by-products in concrete production is of a great important. This approach offers alternatives substitutes for natural aggregates, leading to more sustainable concrete and greener design. This work presents a comprehensive review of using Annaba blast furnace slag, considered an industrial waste, in the fabrication of concrete, with particular reference to using slag concrete as a filling material in lightweight steel construction, highlighting its sustainability and environmental benefits. This study reviews the existing literature on using slag in the concrete and cement industries. It assesses the content and results of prior studies and presents the expected impact of these by-products. The aim is to assess and explore the potential for reuse of steel slags, which are difficult to store and can be released into the environment. Both the economic and environmental benefits were investigated.

KEYWORDS: Blast furnace Slag, Concrete, Slag stone concrete, sustainability, recycling materials.

INTRODUCTION

Concrete is a construction material that is widely used throughout the world Along with water and cement, aggregate is one of the primary concrete components, accounting for approximately 55% to 80% of the volume of concrete.

Concrete aggregates come in two main types: coarse, with particle sizes exceeding 4.75 mm (e.g., gravel), and fine, smaller than 4.75 mm (e.g., sand). They are typically extracted from natural deposits or crushed from larger rocks. During hydration, the coarse aggregates bond with the cement paste to form concrete, while the fine aggregates fill the voids between them, contributing to strength and workability.

The significant growth in the global construction industry is leading to a rapid annual increase in the consumption of natural aggregates. As a result, aggregate reserves are being rapidly depleted; the global concrete industry uses an estimated 8 to 12 billion tonnes of natural stone per year.[25],[26] Unless viable alternatives are developed in the near future, this extensive use of natural aggregates will inevitably lead to environmental degradation.

Consequently, it is imperative to develop and provide alternatives to natural aggregates by studying the viability of employing industrial waste and by-product such us slag in concrete production. This would result in the production of more environmentally-friendly concrete and the implementation of more sustainable design practices.

The production of steel, necessary for our modern world, has a hidden environmental impact. Approximately 15-20% of the iron used in steel mills is turned into slag. This by-product is usually dumped in special storage areas, which poses a threat to the environment.

The amount of steel slag generated each year is continuing to increase as steel production expands worldwide. Over the previous five years, the average annual production of steel worldwide has exceeded 1.6 trillion tonnes, and reached nearly 2 trillion tonnes in 2019 alone,[12] according to a recent report by the World Steel Association, India, China, and Japan stand as the leading steel manufacturers. Over fifty per cent of the world's production is manufactured in China.[25], [30], [27] Despite its beneficial properties, the global use of steel slag is still insufficient, at less than 30%. With the projected growth of steel production, more than 300 billion tonnes of steel slag waste could be generated annually. This necessitates increased efforts in recycling and utilizing this waste material to mitigate its potential harm to both human health and the environment.[12]

1. Slag types and treatment

Slags are a residual material that is produced as a result of metallurgical processes, and it primarily consists of calcium silicates and aluminosilicates.[11] The most frequently generated type of slag in the steel and iron industry is known as blast furnace slag, and it is a glassy and granular substance created through rapid cooling the molten slag in water (e.g., immersion),[23], [10]

Slags result from the cooling of molten blast furnace slag, typically by immersion in water. The resulting type and structure of the slag depend on the cooling technique employed. Two types of slag can be produced as a result of the cooling methods: granules and crystals.[23]

- **Granulated slag** is formed when molten metal is rapidly cooled, resulting in an amorphous, glass-like structure. This quick cooling process prevents crystal formation, and maintains the slag in a solid state. This type of slag is highly valuable for its small particle size and pozzolanic properties.

Figure 1: Granulated slag.[5]

- **Crystallized slag,** on the other hand, is produced by a slower cooling process. This allows the molten slag to crystallize and form a distinctly different structure. Crystalized slag can be mixed with natural sand to make concrete as gravel.

Figure 2: Crystallized slag.[5]

2. The Slags from Annaba blast furnace

The Annaba steel complex, located in the east cost of Algerian, produces a significant amount of industrial waste. These wastes are of two types.

- Non-recyclable wastes: This includes materials that cannot be re-used and must be landfilled.
- Recyclable by-products: This category includes materials such as steel slag. These can be processed and used in various other industries.

4.2.1. The Production of slag from Annaba blast furnaces

The Annaba blast furnace generates a substantial annual volume of slag reaching 600,000 tonnes, with 430,000 tonnes is granulated and 170,000 tonnes is crystallized slag.[22]

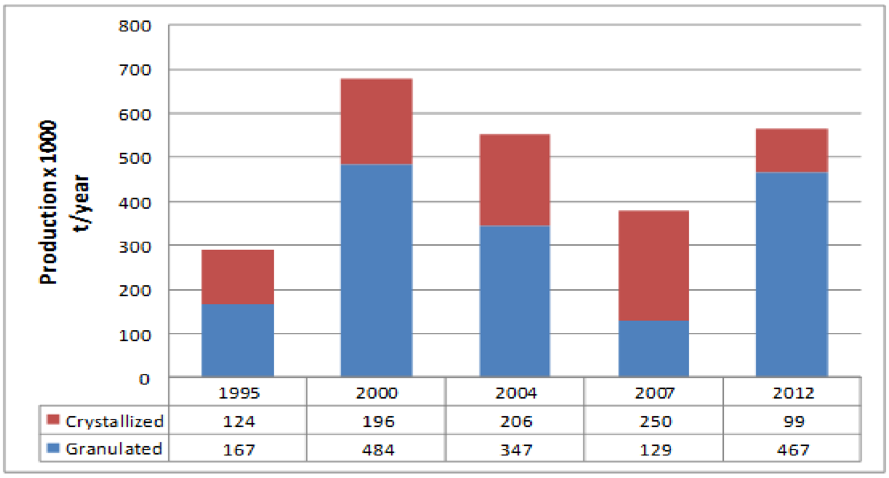


Figure 3: Production of slag from Annaba blast furnaces.[22]

Blast furnace slag was considered a waste product to be dumped at the beginning of industrial development. This was the case in the 1970s, when the Annaba steel complex started operating.[5], [22]

Since the 1980s, the by-product has been partially reused in cement production for granulated slag and in some road foundation projects for crystallised slag.[5]

4.2.2. The environmental impacts of Annaba slag production

The negative impact of the production of slag on the environment is illustrated in Figure 4 and can be summarised as follows.

- Air pollution: The production of slag can result in the release of air pollutants. These include sulphur dioxide and nitrogen oxides that can cause respiratory and other health problems.
- Water pollution: The production of slag can also release water pollutants, such as heavy metals and other chemicals, which can harm aquatic life.
- Solid waste: The production of slag generates a large amount of solid waste, which can take up valuable land space and pose a risk of environmental contamination if not properly managed.

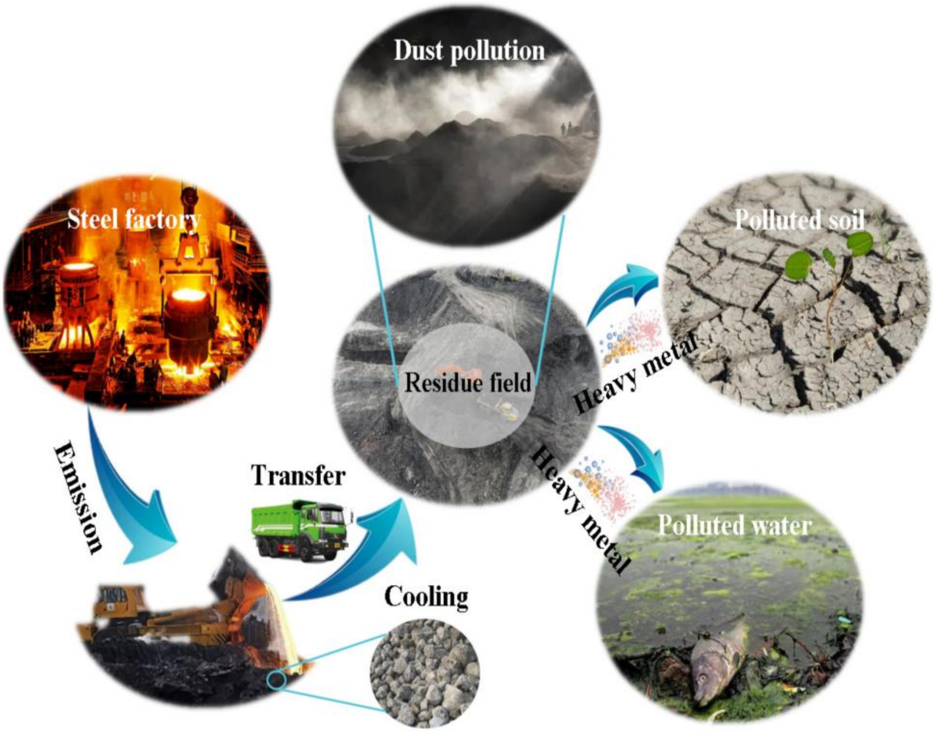


Figure 4: The environmental impact of unused steel slag.[25]

3. The use of Annaba slag in concrete production

Slag, a by-product of iron production, holds immense potential as a valuable resource. Proper management is crucial to safeguard the environment from its potential negative impacts. By implementing responsible treatment, recycling, and landfilling practices, we can minimize slag's environmental footprint and preserve our natural resources.

Extensive research has explored various methods for recycling blast furnace slag, particularly exploring its potential applications as a cement compound or aggregate in concrete production.[24] [10] [31]

4.1. Cement Component

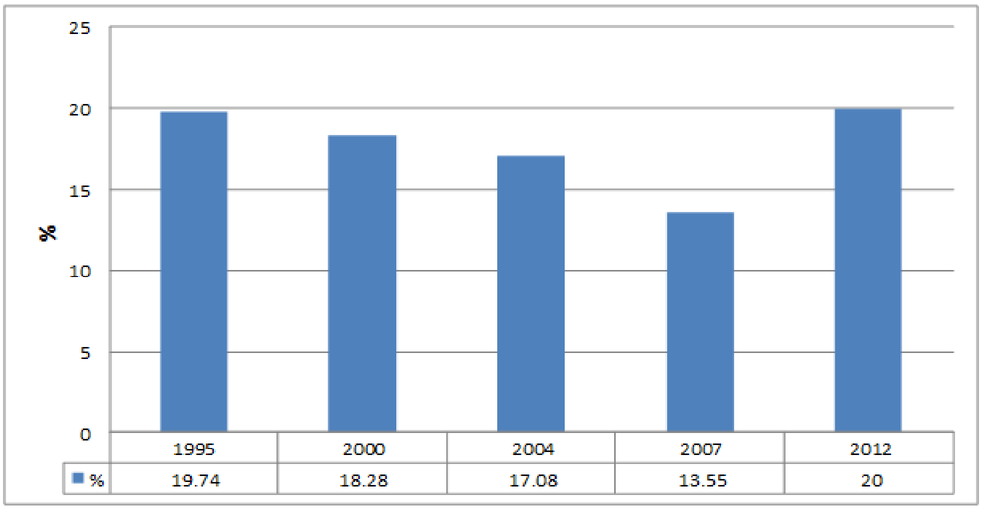
In the early 20th century, VICAT[5] discovered the potential of hydraulic slag and proposed its use in cement production. Inspired by this innovation, the German steel industry developed its own process around 1900, involving a mixture of lime and crushed slag, paving the way for wider adoption of this sustainable material.

Pioneering the use of granulated slag in cement, PRUSSING[5], [22] in 1882 innovation revolutionized the industry. The slag is typically mixed with clinker in impressive proportions, ranging from 5 to a remarkable 90%, to produce standard slag cement.

The first slag cements produced in France date back to 1890. In Algeria, incorporating slag into cement production is a relatively new practice, having only begun in the 1980s with the introduction of CPJ cement. This blended cement was comprised of 70-80% clinker, 15-25% granulated slag, and 5% natural gypsum.[5], [22]

The first incorporation of granulated slag from Annaba blast furnaces into the production of cement was successfully carried out in 1982 at the HADJR SOUD cement plant located in east of Algeria. This progress came after positive test results in the laboratory, validated by additional research[44], and subsequent industrial testing. However, the adopted inclusion rate of 15% proved insufficient to absorb the on-going production of granulated slag, leading to its accumulation. Currently, 2 million tonnes of slag are stored at the complex.[5], [22]

Figure 5 presents the annual percentage of granulated slag utilized by the HADJR SOUD cement factory from 1995 to 2012.[22]



	1995	2000	2004	2007	2012
■ %	19.74	18.28	17.08	13.55	20

Figure 5: The annual percentage of granulated slags used in cement.[22]

Slag utilization in cement production offers a range of environmental and performance benefits, making it a sustainable and valuable component in the construction industry. Its ability to enhance concrete's durability, workability, strength, and permeability, while reducing environmental impact and cost, makes it a compelling choice for a wide range of applications. Careful consideration of its limitations, such as setting time, early strength, and color, is essential for optimizing its use in specific projects. As research and development continues, slag is set to play an ever-increasing role in shaping a sustainable future for construction.

4.2. CONCRETE AGGREGATE

Granulated slag offers diverse applications in the concrete industry. It can be incorporated as an active component in hydraulic concrete mixes, serve as an alternative to conventional concrete sand (either natural or pre-crushed), or be utilized in its crystallized form as an aggregate for creating sustainable slag stone concrete (SSC).

Dr Behim[5] at the laboratory of the University of Annaba carried out the first experimental performance tests of the Slag Stone Concrete (SSC) using the slag from the Annaba blast furnace.

As part of this study, the compressive strength, splitting tensile strength and gas permeability of slag concrete were determined in a series of tests. These results were analysed in comparison with a reference concrete mixture incorporating ordinary aggregate.

In this study, only the results of the strength tests will be presented.[5]

Four concrete samples were designed and prepared for this investigation, employing different ratios of natural and slag aggregates in each mix.

- Mix 1: A Standard concrete mixture made with natural sand and ordinary gravel.
- Mix 2: An Improved concrete mixture composed of natural sand, granulated slag, and ordinary gravel.
- Mix 3: A Slag Stone Concrete mixture made with Granulated slag and Crystallized slag.
- Mix 4: An Improved Slag Stone Concrete containing natural sand, granulated slag, and Crystallized slag.

Six samples were tested for each mix, four compression and two tension.

4.2.1. Results of Compressive Strength

The compressive strength's evolution over time (number of days) for the four concrete mixes as illustrated in Figure 4, increased steadily over time and stabilised at approximately the same level after 180 days, reaching satisfactory values above 35 MPa for all mixes, with ordinary concrete hardening slightly better than slag concrete. This satisfactory performance, exceeding industry standards, confirms the viability of both slag and ordinary concrete for structural applications.

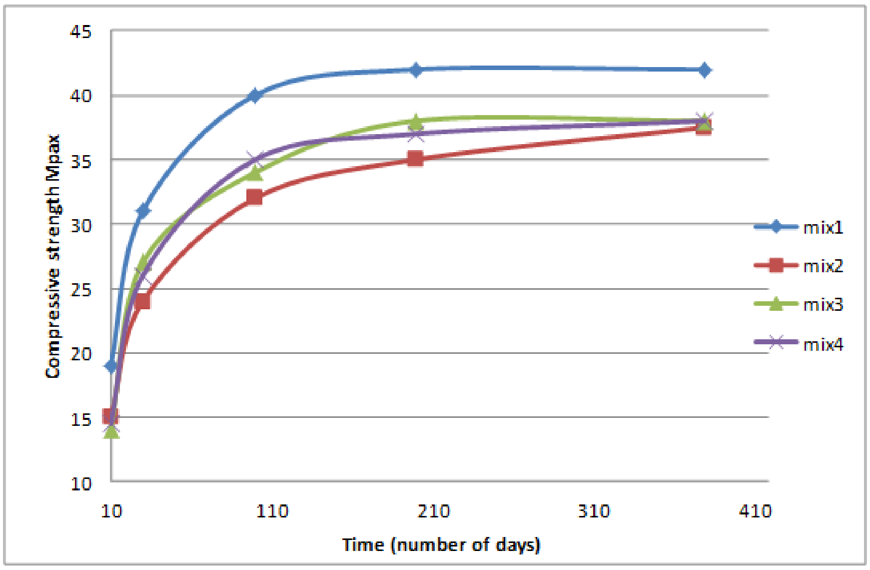


Figure 6: Compressive strength evolution.[5]

4.2.2. Results of Tensile strength by splitting

The splitting tensile strength of slag concrete exhibits a distinct behaviour compared to its compressive strength. As illustrated in Figure 5, mixes 2, 3, and 4 (slag concrete) show a significantly faster increase in splitting tensile strength than mix 1 (standard concrete).

Concrete mixes 3 and 4, composed mainly of both granulated and crushed slag; demonstrate the superior influence of aggregate properties on tensile strength. After 360 days, they exhibit the highest splitting tensile strength, highlighting how the inherent nature of aggregates directly impacts the formation and performance of the cementation matrix, the key determinant of tensile strength. Furthermore, the slopes of the curves clearly demonstrate that the hardening rates of the slag concrete mixes (2, 3, and 4) exceed those of the standard concrete (mix 1).

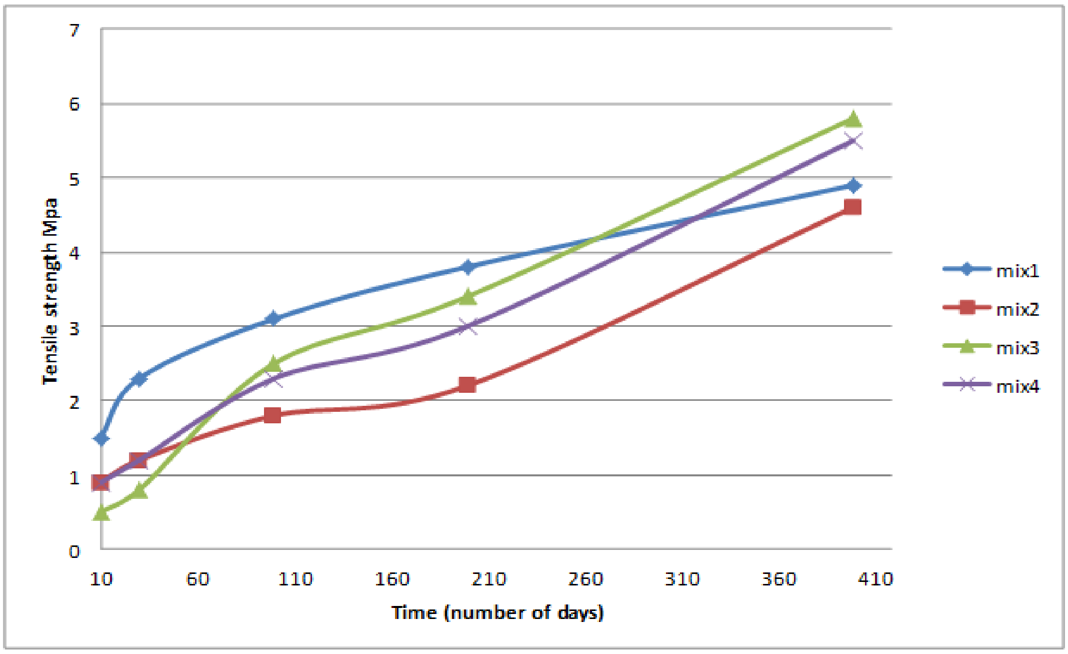


Figure 7: Tensile strength evolution.[5]

The replacement of natural aggregates with granulated and crystallised slag in mixes 3 and 4 resulted in significantly higher strength compared to the improved concrete mix 2 containing only natural sand, granulated slag, and ordinary gravel. This suggests that crystallized slag aggregate plays a significant role in enhancing the interconnectivity of the cementation matrix, leading to the observed substantial increase in splitting tensile strength.

In conclusion from the previous tests results, the benefits of using granulated and crystallised slag in concrete (SSC) production can be summarised as follows.

- Granulated Slag
  - Hydraulic Properties: In concrete, granulated slag can partially substitute cement. Contributing to its overall strength and durability. Its slow hydration process reduces the risk of cracking and allows for long-term strength development.
  - Active Component in Sand: Unprocessed or pre-crushed granulated slag can be used as a sand replacement, reducing the need for natural sand extraction and promoting sustainability.
  - Environmental Benefits: Utilizing granulated slag in concrete reduces the carbon footprint of construction projects compared to traditional methods.

- Crystallized Slag: A Sustainable Alternative.

- Aggregate for SSC: Crystallized slag, a coarser by product, can be crushed and used as a sustainable aggregate in SSC. This reduces reliance on natural aggregates and contributes to resource conservation.
- Durability and Strength: SSC exhibits excellent durability and strength characteristics, making it suitable for various construction applications.
- Cost-Effectiveness: Utilizing slag as an aggregate can be more cost-effective than using natural aggregates, particularly in regions with limited access to traditional materials.

4.3. Filler material for composite steel tube structures

The growing interest in composite steel-concrete structures in recent years has been driven by the concerns about sustainability and the need for efficient construction., these structures, employing a combination of materials such as steel and concrete, have attracted considerable attention. This synergistic combination is now utilized in the structure made of steel tubes filled with concrete, offering numerous benefits, including improved strength, fire resistance and cost effectiveness.[28]

Composite structural elements combine the high tensile strength and ductility of steel with the high compressive strength and stiffness of concrete, this combination allows the composite member to benefit from the advantages of each material.[18] This enables them to achieve superior strength-to weight ratios, enhanced fire resistance, and improved deflection under load, making them a valuable solution for various structural applications. The steel tube acts as a mould to cast concrete, hence reducing construction costs by eliminating the need for further formwork. The tube eliminates the need for separate reinforcing bars by acting as both the longitudinal and transverse reinforcement for the concrete core. In addition, the continuous confinement offered by the steel tube significantly enhances the concrete core strength and ductility.[1] The confinement provided by this method effectively delays local buckling of the steel tube, thus preventing it from collapsing inward. At the same time, the steel tube also acts as a barrier, preventing the concrete from breaking apart.

However, only a few investigations have been carried out on steel components welded by cold forming, and filled with sustainable materials. J. Zeghiche's study[20] [21] investigated the use of slag concrete as a filling material to overcome the various imperfections resulting from cold formed sections assemblies. The study revealed a gain in strength of up to 2, which linearly decreased with increasing tube height.

Experimental tests on the mechanical and thermal performance of steel stubs filled with slag stone concrete (composite structure) were carried out by Dr D. Beggas and J. Zighiche in the civil engineering laboratory of the University of Annaba.[2], [3] This study consisted of two parts.

- The first part of the experimental tests investigated the mechanical performance of steel stubs filled with slag concrete. This study tested thin-walled rectangular steel stubs filled with concrete made from slag stone. These stubs were made of two U-shaped cold-formed steel plates welded to create a box measuring 100 x 70 x 2 mm. The study investigated the influence of three factors: stub height (ranging from 50 to 500 mm, concrete infill presence, and the location of the weld fillet.

Tube manufacture cross section presented in figure 8.

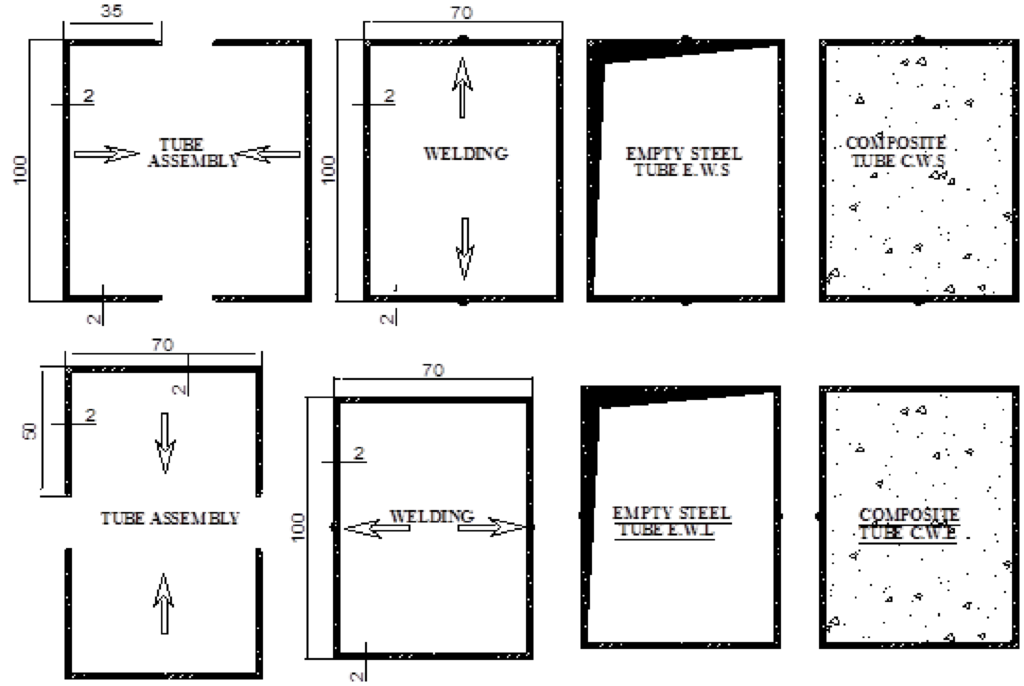


Figure 8: Tube manufacture cross section (Empty and filled).[3]

The tests were conducted 28 days after curing of the concrete infill, 28 stub specimens - half empty and half filled with crushed crystallized slag were tested using a universal testing machine (UTM) under axial compression until failure. The study aimed to determine the ultimate load capacity of the composite sections formed by steel and concrete infill. It also assessed the performance of crushed crystallized slag as a substitute for conventional aggregate in concrete for these composite sections.

The conventional sand and aggregates were substituted with crystallised slag, the compressive strength after twenty-eight days of the self-setting concrete (SSC) was found to be 35 (MPa), whereas the yield strength of the steel used was 300 MPa. The Young's modulus of the steel was determined to be 20.5 (GPa). Throughout the casting process, the concrete was subjected to high-frequency, low-amplitude external vibration on a shaking table for 2-3 minutes to eliminate air bubbles. Both top and bottom surfaces of the composite stubs were then ground to ensure level contact between steel and concrete, enabling uniform load transfer during testing.

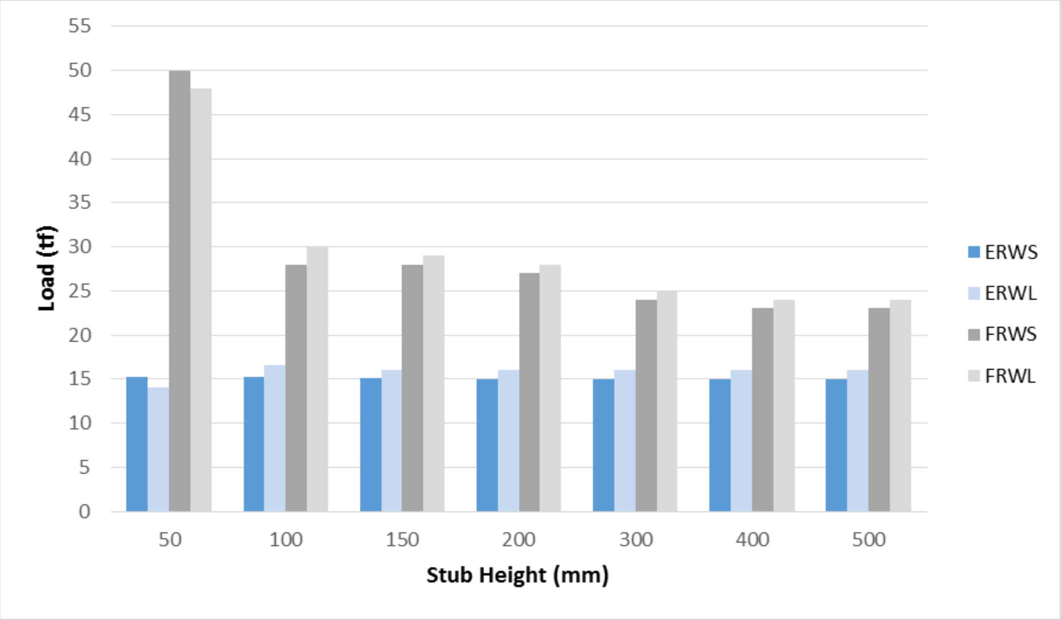


Figure 9: Comparison of Experimental Failure Loads.[3]

Where.

- ERWS: Empty rectangular steel stub samples, welded on the small sides.
- ERWL: Empty rectangular steel stub samples, welded on the Large sides
- FRWS: Filled rectangular steel stub samples, welded on the small sides.
- FRWL: Filled rectangular steel stub samples, welded on the Large sides.

The results of the tests revealed that Slag stone concrete filled stubs, which were tested 28 days after being cast, demonstrated excellent performance and achieved maximum loads that either exceeded or close to the expected maximum failure load. The filler concrete effectively increased the ultimate bearing load and significantly delayed local buckling, acting as an internal bracing system, providing additional support and stiffness to the steel walls. Short Samples experienced failure with test loads that were roughly double the predicted failure load. This phenomenon is attributed to the concrete core being subjected to a condition of constrained stress, enabling it to achieve a compressive strength about three times higher than that of concrete after 28 days. This represents a strong evidence of the positive slag stone concrete core impact and the synergistic effect of the steel-concrete composite.[3]

- The second part of the study investigates the thermal performance of lightweight steel buildings. By measuring the thermal properties of this innovative material and analysing wall panels using advanced network methods[8,13,19,29], exploring the thermal resistance of walls incorporating steel frameworks filled with slag stone concrete.

Four sets of samples with varying slag aggregate size were prepared as displayed in table1, All series achieved a consistent 28-day compressive strength in laboratory tests. The thermal conductivity of each mix was measured using the Hot Disc method, as described in detail by[14,15 16], a transient technique employing a thin-film Kapton sensor that is placed between two samples and heated with a short-duration electrical current. This rapid, non-destructive approach minimized preparation and provided accurate measurements, ideal for evaluating the thermal properties of diverse slag stone concrete mixes, (figures: 10 and 11).

Table 1: Crushed slag stones sizes for each Mix.[2]

Mix No	Crushed slag stones sizes	Number of samples
Mix 1	10 mm	3
Mix 2	12 mm	3
Mix 3	15 mm	3
Mix 4	20 mm	3

Figure 10: Hot disk measurement process.[2]

Figure 11: Process of samples measurement.[2]

Three compact samples each 50mm x 50mm x 150mm were prepared from each concrete mix for subsequent thermal conductivity measurements.

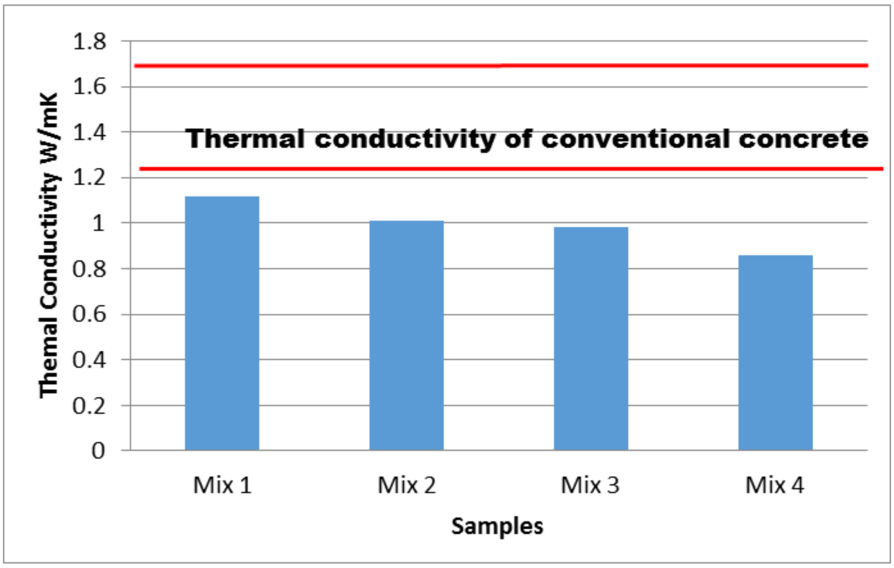


Figure 12: Measured Thermal Conductivity.[2]

Three samples of each concrete mix were tested. Figure 12 reveals that decreasing aggregate size in our concrete mixes significantly reduced thermal conductivity. Measured values ranged from 0.86 to 1.13 W/ (m-K), a remarkable 48% decrease compared to conventional concrete. This thermal performance translates to substantial potential for energy savings in buildings, leading to reduced heat loss and lower energy consumption.

Furthermore, the improvement in thermal capacitance plays a crucial role in reducing the impact of the daily temperature swings (5°C to 45°C). This translates to a potential reduction in energy consumption for light steel buildings, while promoting sustainability through the use of recyclable materials.

4. CONCLUSIONS

This research demonstrates the viability of utilizing Annaba blast furnace slag in concrete production, offering substantial environmental and performance benefits. Slag's ability to enhance concrete strength, durability, and workability while reducing environmental impact and cost makes it a compelling choice for a wide range of applications. Research continues to optimize slag use, exploring ideal slag-to-cement ratios and alternative aggregates to achieve both high mechanical strength exceeding specific thresholds and improved thermal properties for sustainable and energy-efficient buildings. Overall, slag offers a multitude of advantages: Reduced environmental impact: Minimizing natural resource consumption and carbon emissions, slag utilization contributes to a more sustainable construction sector. Enhanced concrete properties: Granulated slag's hydraulic properties and crystallized slag's aggregate potential improve concrete strength, durability, and overall performance. Cost-effectiveness: Slag can be a cost-effective alternative to traditional materials, further enhancing its appeal.

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