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Alternative Fine Aggregates to Natural River Sand for Manufactured Concrete Ensuring Circular Economy

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Abstract: To address SDG12 (ensure sustainable consumption and production patterns), and to provide technical evidence for alternative concrete constituents to traditional natural river sand, stone fine aggregate (SFA), brick fine aggregate (BFA), ladle-refined furnace slag aggregate (LFS), recycled brick fine aggregate (RBFA), and washed waste fine aggregate (WWF), ready-mix concrete plants were investigated. Concrete and mortar specimens were made with different variables, such as replacement volume of natural sand with different alternative fine aggregates, water-to-cement ratio (W/C), and sand-to-aggregate volume ratio (s/a). The concrete and mortar specimens were tested for workability, compressive strength, tensile strength, and Young's modulus (for concrete) at 7, 28, and 90 days. The experimental results show that the compressive strength of concrete increases when natural sand is replaced with BFA, SFA, and LFS. The optimum replacement amounts are 30%, 30%, and 20% for BFA, SFA, and LFS, respectively. For RBFA, the compressive strength of concrete is increased even at 100% replacement of natural sand by RBFA. For WWF, the compressive strength of concrete increases up to a replacement of 20%. Utilizing these alternative fine aggregates can be utilized to ensure a circular economy in construction industries and reduce the consumption of around 30% of natural river sand.

Keywords: circular economy; compressive strength; fine aggregate; material flow analysis; workability

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1. Introduction

The concept of 'cleaner production', a strategy to promote environmental sustainability in industrial processes, has recently been introduced to ensure the sustainability of the environment for future generations. The concrete industry significantly consumes natural, non-renewable resources, so sustainability has become a growing concern that needs to be considered. The concept of the circular economy (CE) has become increasingly popular in recent years. This economic system relies on business models that eliminate the idea of a tangible product reaching the end of its useful life. Instead, it focuses on reducing waste, reusing materials, recycling, and recovering resources through manufacturing, distribution, and consumption processes and finding alternative sources [1]. The aim is to repurpose, repair, and recycle material to create a new form that may be used effectively. This process reuses recycled materials to generate a new product after manufacturing [2,3]. The product does not need to be identical. It promotes the use of recycled resources and the implementation of environmentally sustainable technologies. Utilizing recycled materials can help the construction industry decrease its reliance on natural river sand and minimize materials in landfills. This approach also helps to protect river ecosystems [4]. It supports the goals of SDG 12 by promoting the efficient use of resources, reducing waste, and encouraging innovation and sustainability in the building industry [5].

In 2023, global cement production reached around 4.1 billion tons. In 1995, the worldwide production of cement was just 1.39 billion tons, demonstrating the construction sector's substantial growth [6]. Aggregates are the primary component of the materials that are utilized in concrete production, comprising around 75% of the overall volume of concrete [7]. Consequently, the significant aggregate demand is mainly fulfilled by utilizing natural resources. The rapid development of urban infrastructure has led to a rise in the exploitation of natural resources over the years, resulting in the depletion of these resources to a significant extent. This depletion is generating serious environmental consequences [8]. The construction sector of Bangladesh is also subject to the same conditions. Concrete's mechanical and durability properties depend heavily on the quality and quantity of sand used as a filler [9,10]. With global restrictions on river sand mining [11–13], there is an urgent need for alternative materials. The research presented here is essential in addressing this pressing need.

Bangladesh, a mainly plain and deltaic region, faces a scarcity of resources for coarse and fine aggregates required for concrete production. Stone aggregate is not readily available, so clay bricks are commonly used as a substitute for coarse aggregate, significantly contributing to environmental pollution. A series of studies have investigated potential alternative materials for use as coarse aggregate. River sand, primarily utilized as a fine aggregate in concrete, is commonly acquired by the process of dredging along the riverbed. The fine aggregate use in Bangladesh is around 80 million tons annually (cement production in Bangladesh is 10 MT per annum [14], assuming fine aggregate of 800 kg/m^3). Due to extensive construction activities associated with numerous large-scale projects, as well as government and private initiatives, there will likely be a substantial reduction in the availability of natural fine aggregate soon. This research is significant in the context of Bangladesh's construction sector as it provides insights into potential alternative fine aggregates, which can help mitigate the impact of the depletion of natural resources and contribute to sustainable construction practices.

Hence, it is very important to investigate alternatives of fine aggregate to encourage sustainable advancement of construction materials. Several resources can be utilized to make concrete with alternative finer materials. For example, stone dust produced while crushing stones can be an alternative resource. A good number of studies have already been conducted on the utilization of this material in concrete [15–19]. Some researchers also attempted to produce high-performance concrete by incorporating stone dust as fine aggregate in concrete [20]. Different attempts were also made to determine the suitability of utilizing stone fine aggregate in producing asphalt mix and making lightweight aggregate for construction purposes [21,22]. However, few attempts were made where various concrete mix proportions were investigated for different replacement ratios of stone fine aggregate [23–25]. As such, it is understood that a detailed investigation is required to understand the full potential of stone dust as a fine aggregate in concrete.

Brick fine aggregate is another alternative to fine aggregate that may be utilized in concrete. Bangladesh has over 7000 brick manufacturers due to the high demand for bricks as construction material [26]. The process of pulverizing these bricks at construction sites generates a substantial quantity of fine materials, which are often not fully utilized. Although many attempts were made to understand the suitability of crushed brick chips as coarse aggregate in concrete, very few studies were found that examined the utilization of brick fine aggregate as fine aggregate in concrete [27–31]. Therefore, to assess the feasibility of employing brick fine aggregate in the form of fine aggregate in concrete, a thorough investigation is necessary.

Ladle-refined furnaces are employed to refine molten steel in steel industries. LF slag, or refining slag, is a basic slag generated during the final phases of steel production when the steel is desulfurized in the transport ladle during the secondary metallurgy process.

Assuming that ladle-refined furnace slag could be utilized as fine aggregate in concrete, the feasibility of this use must be assessed. Annual steel production is about 9 MT in Bangladesh. According to The Business Standard, per capita steel consumption is expected to rise from 45 kg in 2022 to above 100 kg by 2030. Production capacity is rapidly increasing with demand, with an annual growth rate of 10% [32]. Steel slag is a significant industrial by-product in steel production, which is a result of the extensive manufacturing of steel. Many researchers have studied the suitability of incorporating fine slag as a fine aggregate in concrete [33–39]. Few studies have examined the suitability of ladle-refined slag as a fine aggregate in concrete [40,41].

Fine aggregates can also be sourced from demolished concrete structures, conserving significant natural resources. In addition, it can also contribute to reduction of waste and address challenges related to the disposal of demolished concrete, resulting in cost savings for the local government. Furthermore, it supports the achievement of Sustainable Development Goals (SDGs) 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation), 11 (Make cities and human settlements inclusive, safe, resilient and sustainable), and 12 (Ensure sustainable consumption and production patterns), thereby promoting a sustainable future. Utilizing concrete waste from demolished structures, a mixture of 50% recycled aggregates and 50% fresh aggregates may be used to construct roadway sub-bases, which will facilitate the attainment of environmental, economic, and social sustainability [42]. By recycling demolished concrete, it is possible to conserve 20% of the usual amount of virgin aggregate. If technological breakthroughs and broad adoption of recycled aggregate occur, the utilization of ordinary aggregate will become redundant, assuming complete recycling of all demolished concrete for future construction purposes. The deconstruction of low-rise structures is resulting in an upward rise in the quantity of demolished concrete in Bangladesh, driven by the heightened demand and flourishing real estate industry. The utilization of recycled aggregate can alleviate the burden of disposal, decrease expenses, and diminish the consumption of primary aggregate. The utilization of pulverized recycled brick aggregate from two condemned structures, which were 50 and 70 years old, was the focus of the investigation. Studies related to the recycling of demolished concrete are generally found for stone chips used to make concrete [43,44]. A study was conducted on the recycling of destroyed brick aggregate concrete as coarse aggregate [45]. Further investigation is necessary to examine the properties of concrete developed with recycled brick aggregate as both coarse and fine aggregate.

The Ready-Mix Concrete (RMC) industry is actively looking for new approaches to improve resource efficiency by utilizing returned concrete as a substitute for fine aggregates. Multiple research projects have proven the possible viability of implementing this approach. In their study, Correia, Souza, Dienstmann, and Segadães (2009) discovered that including fresh concrete waste (FCW) as a substitute for some of the sand in concrete did not compromise its compressive strength and water absorption, even though it did result in decreased workability [46]. Ferrari, Miyamoto, and Ferrari (2014) demonstrated that coarse aggregates derived from recycled concrete can substitute up to 30% of new aggregates without impairing the quality of the concrete [47]. Rughooputh, Rana, and Joorawon (2017) found that using the right amount of FCW can help reduce adverse effects on concrete properties [48]. Anastasiou, Papachristoforou, Anesiadis, Zafeiridis, and Tsardaka (2018) as well as Chatveera, Lertwattanaruk, and Makul (2006) investigated cement sludge fines and sludge water, respectively, and observed that careful proportioning allows for partial replacement [49,50]. Kou, Zhan, and Poon (2012) found that using crushed hardened concrete debris impacted compressive strength and durability characteristics [51]. Additional research is required to analyze the characteristics of concrete produced using washed waste fine aggregate as fine aggregate.

This paper summarizes the authors' insightful information on several comprehensive research studies and previous investigations on sustainable construction materials, primarily emphasizing the alternative fine aggregates that may be utilized as replacements for natural river sand. In addition, the paper establishes the link between this study's outcomes and the concept of the circular economy. Furthermore, a material flow analysis of the alternative fine aggregates is also established.

2. Materials and Methods

2.1. Materials

2.1.1. Stone Fine Aggregate (SFA)

To investigate the feasibility of using stone fine aggregate as a substitute for conventional fine aggregate, stone fine aggregate (SFA) was sourced from a nearby stone crusher plant in Dhaka. The process of crushing stone lumps resulted in the production of SFA as a by-product of crushed stone aggregate.

The research investigates 100 mm × 200 mm cylindrical concrete specimens. The specimens were created by gradually substituting natural river sand with stone fine aggregate, ranging from 0% to 100%. The volume ratio of fine aggregate to total aggregate (s/a) was set at 0.37. Two different water-to-cement ratios (W/Cs) were used, specifically 0.40 and 0.45. The cement content varied among 365 kg/m^3, 410 kg/m^3, 440 kg/m^3, and 470 kg/m^3, with 0%, 30%, and 100% replacement levels. Coarse aggregate was made from crushed stone. Mortar specimens of 50 mm × 50 mm × 50 mm were made with varying percentages (0%, 10%, 20%, 30%, 50%, and 100%) of stone fine aggregate (SFA) replacing natural sand. In these instances, the water-to-cement ratios (W/Cs) were 0.485 and 0.40 for various replacement percentages (0%, 30%, and 100%). The fine aggregate to cement ratio (s/c) was 2.75, and the cement content was 365 kg/m^3. The detailed results were summarized in a master's thesis [52].

2.1.2. Brick Fine Aggregate (BFA)

To investigate the effects of brick fine aggregate (BFA) as an alternative to natural sand, brick fine aggregates (denoted as S1, S2, and S3) were acquired from three distinct sources near Dhaka to make concrete specimens.

The research investigates cylindrical concrete specimens of size 100 mm × 200 mm. The natural river sand was progressively replaced by 0%, 10%, 20%, 30%, 40%, and 50% of alternatives. The ratio of fine aggregate to total aggregate volume (s/a) was 0.40. The quantity of cement used was 340 kg/m^3, and the water-to-cement ratios (W/Cs) were 0.50 and 0.55. BFA was also utilized to replace natural sand in mortar blocks of size 50 mm × 50 mm × 50 mm × 50 mm at replacement ratios of 0%, 10%, 20%, 30%, 40%, and 50%. The W/Cs were 0.50 and 0.55, while the fine aggregate-to-cement ratio (s/c) was 2.75. The detailed results were summarized in separate articles [53].

2.1.3. Ladle-Refined Furnace Slag Fine Aggregate (LFS)

Samples of slag were collected from a nearby steel manufacturing company in Dhaka to investigate the effects of using ladle furnace slag as an alternative to natural sand. The research investigates cylindrical concrete specimens of size 100 mm × 200 mm made with LFS. Concrete specimens were made by substituting natural sand with LFS. The replacement ratios were 0%, 10%, 20%, and 30%. The fine aggregate to total aggregate volume ratios (s/a) were 0.40 and 0.48, the water to cement (W/C) ratio was 0.45, and the cement content used was 340 kg/m^3. Concrete specimens were made with brick coarse aggregate and induction furnace slag aggregate (IFS) as the primary coarse aggregates. The detailed results were summarized in another article [53].

2.1.4. Recycled Brick Fine Aggregate (RBFA)

This study used demolished brick aggregate of concrete blocks sourced from the remnants of 70-year-old buildings in Dhaka to investigate the effects of using recycled brick fine aggregate (RBFA) as an alternative to natural sand.

For investigation, concrete and mortar specimens were made. The size of the cylindrical concrete specimens was 100 mm × 200 mm. The natural river sand was progressively replaced by varying replacement ratios as 0%, 50%, and 100%. The ratio of fine aggregate to total aggregate volume (s/a) was 0.44. The quantity of cement used was 340 kg/m^3, and the water-to-cement ratios (W/Cs) were 0.35, 0.45 and 0.55. BFA was utilized to replace natural sand in mortar blocks measuring 50 mm × 50 mm × 50 mm at various replacement ratios. The W/Cs were 0.35, 0.45, and 0.55. The detailed results are summarized separately [54].

2.1.5. Washed Waste Fine Aggregate (WWF)

To investigate the effects of utilizing washed waste fine aggregate as a substitute for natural sand, WWF was collected from various levels of the sedimentation basin at a nearby RMC plant in Dhaka. Due to the diverse composition of the material, the samples were obtained from multiple layers of the sedimentation basin and subsequently blended to create a representative sample.

Various combinations of WWF concentrations (ranging from 0% to 20%) and cement types (including CEM Type I (OPC), CEM Type II A-M, and various mixtures of OPC with slag or fly ash) were used to create different mixture proportions. The replacement percentage was restricted to 20% to assess WWF's impact on concrete's hardened properties. To evaluate the comparative reactivity of slag and fly ash in the presence of WWF, the substitution percentages of these components were kept consistent for both types of cement. The replacements were carried out based on absolute volume.

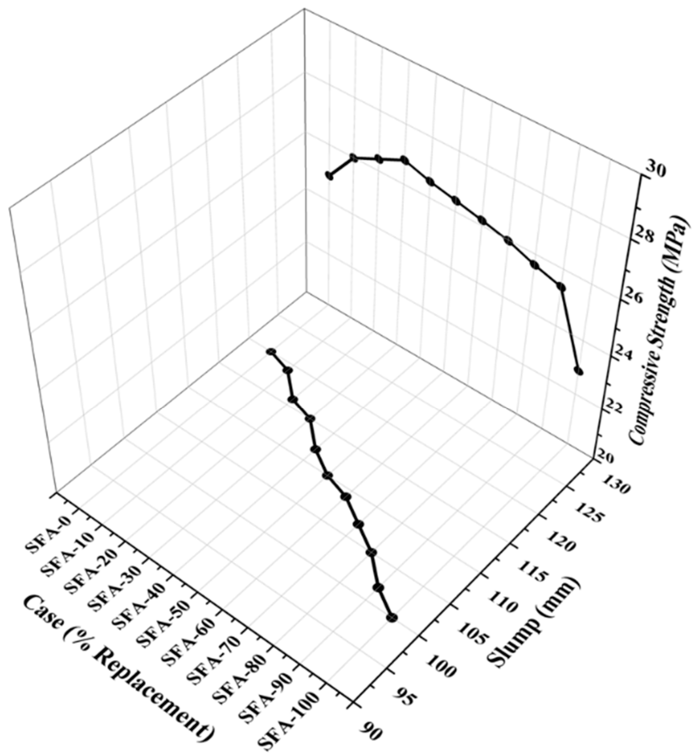
2.2. Methods

Different tests were conducted using the following guidelines for different alternatives of fine aggregate: compressive strength test of concrete (ASTM C39 [55]), compressive strength test of mortar (ASTM C109 [56]), split tensile strength (ASTM C496 [57]), and workability of concrete (ASTM C143 [58]) tests. For fine aggregate, the workability test is a significant factor. As such, relationships between slump and compressive strength were constructed in this article. This research contains a defined approach since it includes several factors and different mix designs; however, controlled cases were established for each alternate fine aggregate. This research examined the sustainable applications of alternative fine aggregates compared to controlled cases using that fine aggregate. There were some logical choices of the percentage of the substitution based on knowledge from the previous experiments and the testing results.

3. Results and Discussions

3.1. Stone Fine Aggregate (SFA) Concrete

Some key results from the master's thesis investigation are summarized in this article. Figure 1 summarizes all the slump values and compressive strength of concrete made with SFA. The workability of fresh concrete decreases progressively as the SFA replacement ratio increases. The fineness modulus were 2.12 and 2.55 for stone fine aggregate and natural river sand, respectively. The higher number of smaller particles in SFA compared to natural river sand requires a larger volume of cement paste to accomplish the desired workability of concrete [59]. The highest compressive strength of concrete cylinder specimens was found after 28 days when the replacement ratio was 30%, with a cement content of 365 kg/m^3 and a water-to-cement ratio of 0.45. The compressive strength of the mortar specimens also showed similar results as the concrete specimens, i.e., the maximum strength at 30% replacement of natural sand by SFA. When the replacement amount crossed 30%, the compressive strength declined. However, the compressive strength of mortar containing 100% SFA was greater than that of mortar containing 100% river sand [52]. Stone fine aggregate, which is finer than natural river sand, is also angular in shape, while natural river sand is spherical; this difference in shape and size enhances concrete's compressive strength by minimizing empty spaces within the mortar matrix and reducing bleeding. It also results in a denser and more uniform Interfacial Transition Zone (ITZ) surrounding the coarse aggregates in the concrete. When the proportion of river sand replaced by SFA exceeds 30%, the requirement for cement paste would escalate due to the relatively smaller sizes of SFA compared to those of river sand. As a result, the compressive strength drops when more than 30% of river sand is replaced with SFA.



Note: SFA-0: 0% replacement with stone fine aggregate,
SFA-10: 10% replacement with stone fine aggregate.....so on.

Figure 1. Stone Fine Aggregate: Slump and Compressive Strength.

Similar results were also observed for the tensile strength and modulus of elasticity of concrete made with SFA [52]. From these results, it can be concluded that SFA can be used for the replacement of natural sand.

3.2. Brick Fine Aggregate (BFA) Concrete

This article summarizes some key results of the previous investigations on BFA. Figure 2 shows the workability and compressive strength of concrete specimens made with BFA collected from three different sources. BFA has more absorption capacity (13.5%, 15%, and 11% for sources S1, S2, and S3, respectively) than natural sand (5.1%). As a result, regardless of the source of brick fine aggregate (BFA), it is found that the workability of concrete decreases as the replacement ratios of BFA increase. Additionally, brick fine aggregate differs from natural river sand in shape. Natural sand is mostly spherical, but BFA particles are angular in shape. The maximum compressive strength of concrete was found at 30% replacement of natural sand by BFA. As brick fine aggregate absorbs more water than natural river sand, the absorbed water inside the brick fine aggregate will help the internal curing of concrete. Eventually, it will help in the early strength development process of concrete. Once the replacement ratio of BFA exceeds 30%, the compressive strength of concrete begins to decrease. Because of the softer nature of brick fine aggregate, the strength of concrete is reduced.

Similar trends in results were also observed for the tensile strength and modulus of elasticity of concrete specimens made with BFA [53].

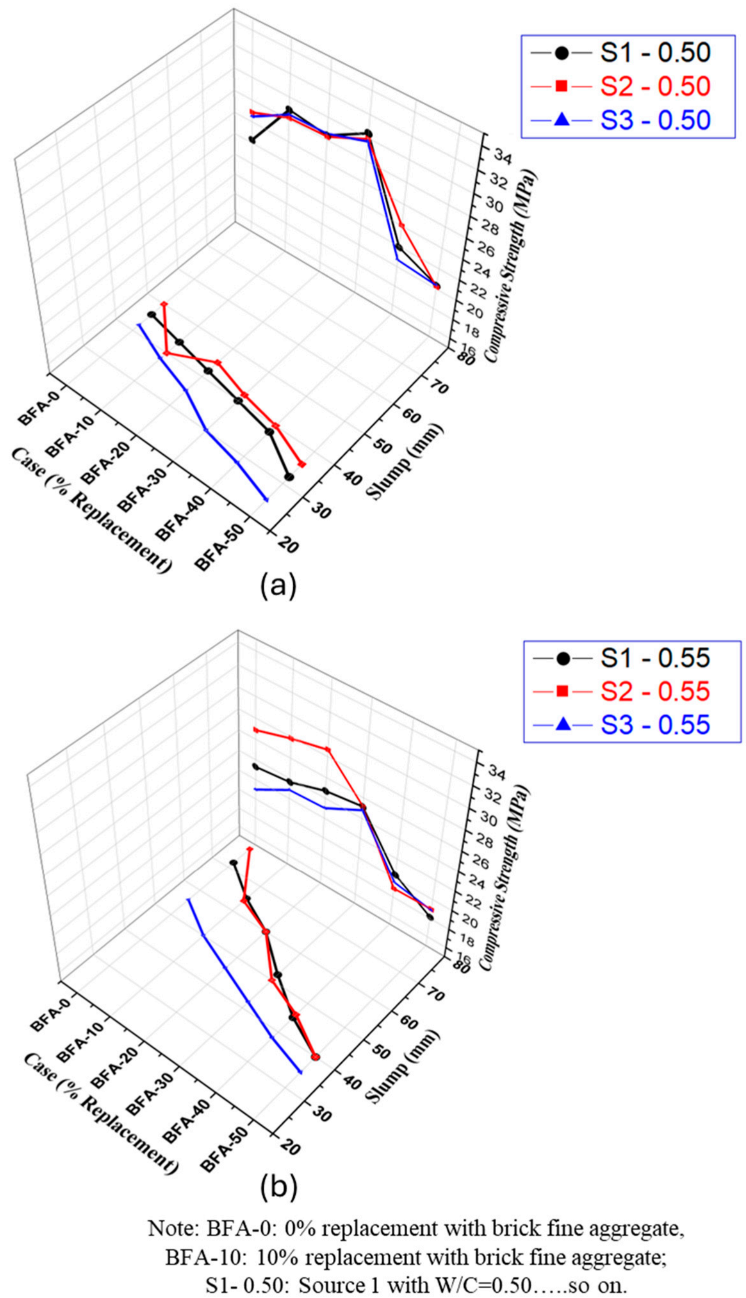
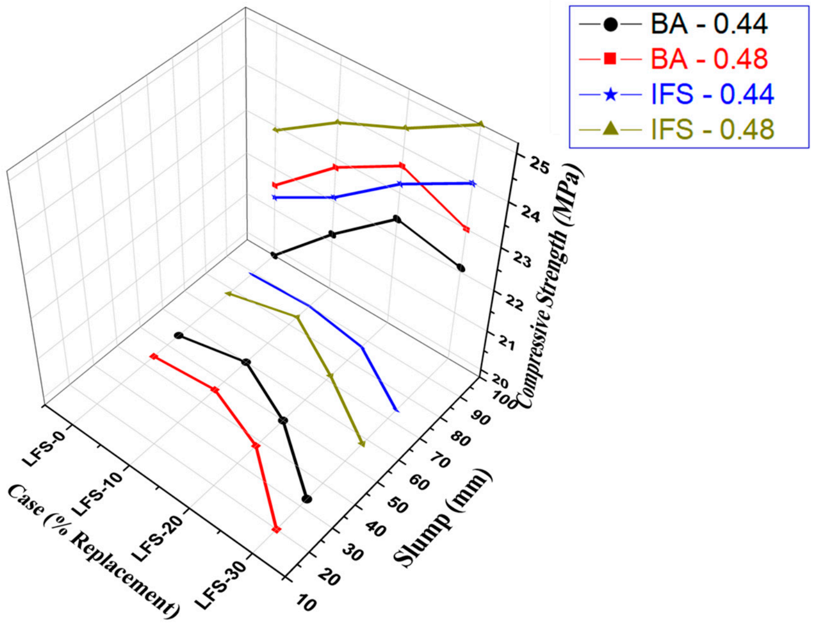


Figure 2. Brick Fine Aggregate: Slump and Compressive Strength (**a**) W/C = 0.50; (**b**) W/C = 0/55.

3.3. Ladle-Refined Furnace Slag Fine Aggregate (LFS) Concrete

This paper summarizes some key results of the research work on LFS. From Figure 3, it is found that the workability of concrete diminishes as the proportion of river sand substituted with LFS increases. The workability of concrete is improved with a small quantity of substitution but decreases with higher amounts of replacement. The preliminary increase in workability can be attributed to the lower absorption capacity (2.65%) of LFS aggregate. The fineness modulus of LFS was 2.36. Nevertheless, the workability diminishes beyond a 10% substitution because of the higher percentage of tiny particles in LFS aggregate compared to river sand. In addition, LFS particles exhibit a higher angularity compared to particles of river sand. This attribute is an additional element contributing to the diminished workability of brick aggregate concrete when the proportion of LFS aggregate exceeds a replacement amount of 10%. When the s/a ratio is 0.48, substituting more than 30% of river sand with LFS in brick aggregate concrete leads to minimal slump.



Note: LFS-0: 0% replacement with ladle furnace slag fine aggregate,
LFS-10: 10% replacement with ladle furnace slag fine aggregate;
BA-0.44: Brick chips as coarse aggregate with f/a=0.44,
IFS-0.44: Induction furnace slag as coarse aggregate with f/a=0.44,…..so on.

Figure 3. LFS: Slump and Compressive Strength.

The compressive strength of concrete specimens, generated by replacing increasing percentages (0%, 10%, 20%, and 30%) of river sand with LFS fine aggregate, was measured after 28 days. The compressive strength of concrete utilizing brick coarse aggregate exhibited an initial rise when the proportion of natural river sand was replaced by 20% of LFS, followed by a slight decrease at a replacement ratio of 30%. Replacing river sand with LFS at a small ratio (less than 20%) led to an improved connection between LFS particles and cement paste because LFS aggregate has more sharpness. Consequently, this resulted in an initial increase in the compressive strength of the concrete. The likely reason for the drop in strength beyond the replacement of 20% could be the increasing quantity of finer particles in the concrete, resulting in lower workability. Because LFS holds a higher percentage of finer particles than river sand, a greater quantity of cement is required to coat the LFS particles thoroughly. As a result, the compressive strength of concrete will diminish when a significant amount of river sand is substituted with LFS. Moreover, the utilization of brick aggregate concrete would result in a substantial reduction in workability if a large amount of river sand is replaced with LFS. This would produce less dense concrete, ultimately leading to a decrease in its strength.

The compressive strength of IFS aggregate concrete exhibited a positive correlation with the substitution percentage of river sand by LFS aggregate, with an increase observed as the substitution percentage went from 0% to 30%. To attain the highest possible compressive strength, additional research is necessary to identify the ideal proportion of river sand that can be replaced with LFS, surpassing the limit of 30%. However, the findings suggest that, in terms of compressive strength, the optimal proportion of river sand substitution with LFS is higher for IFS aggregate concrete than brick aggregate concrete. Because IFS aggregate has pozzolanic properties, it exhibits more strength [60]. IFS aggregate concrete exhibits superior workability retention when a greater proportion of river sand is substituted with LFS in contrast to brick aggregate concrete. As a result, the strength of IFS aggregate concrete diminishes since the workability is significantly reduced when a higher percentage of river sand is replaced with LFS.

The test results showed that the greatest tensile strength and modulus of elasticity were obtained using brick aggregate as the coarse aggregate, with a substitution rate of 20%. Nevertheless, the tensile strength and modulus of elasticity exhibited an upward trend as the proportion of river sand substituted with LFS rose, reaching its peak at 30%, with IFS aggregate serving as the coarse aggregate [53].

3.4. Recycled Brick Fine Aggregate (RBFA) Concrete

This paper highlighted some key findings of the previous study. Figure 4 demonstrates that reducing the water-to-cement ratio (W/C) decreases the workability of concrete. Additionally, it has been noticed that concrete's workability decreases as the replacement ratio of recycled fine aggregate increases. This is due to the higher absorption capacity (15%) of RBFA compared to conventional river sand and due to the shape of the recycled fine aggregate. Natural sand has a spherical shape, whereas recycled fine aggregate has an angular and uneven shape. Regardless of the aggregate type, the compressive strength of concrete is reduced by increasing the water-to-cement ratio. The compressive strength of concrete remains unchanged even when 100% of natural sand is replaced with recycled fine aggregate.

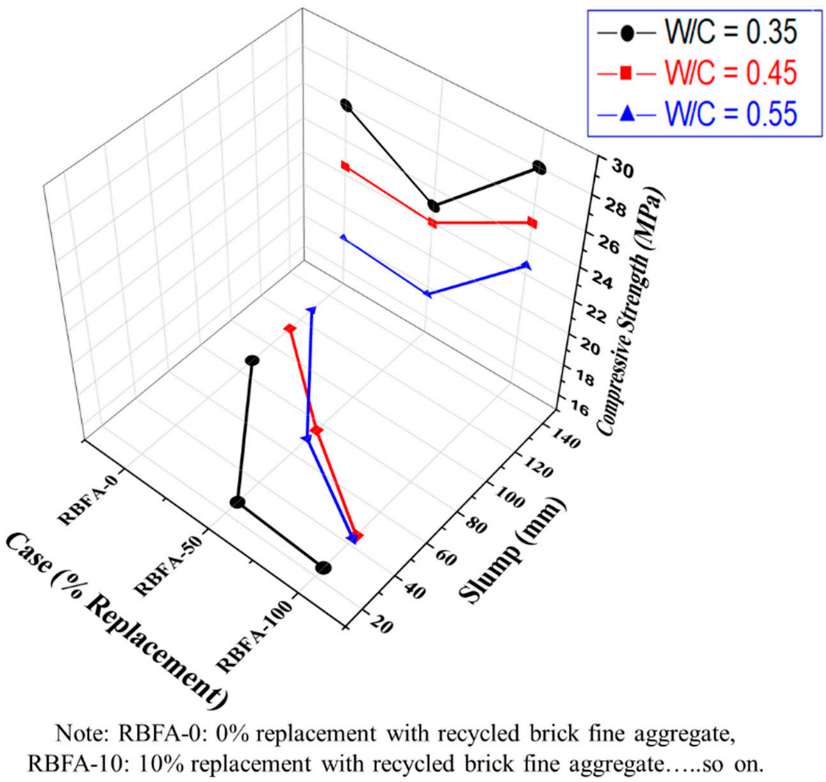


Figure 4. Recycled Brick Fine Aggregate: Slump and Compressive Strength.

As the amount of RBFA increases to 50%, the compressive strength of concrete decreases. When using 100% RBFA, the resulting compressive strength outperforms concrete made only of virgin fine aggregates. The compressive strengths of concretes using natural sand as fine aggregate varied between 18 MPa (2610 psi) and 26 MPa (3770 psi), while concretes prepared with 100% RBFA exhibited compressive strength ranging from 23 MPa (3335 psi) to 28 MPa (4050 psi). Nevertheless, when the quantity of RBFA rises, the workability decreases. The slump value ranges from 84 mm to 124 mm for concrete made only with river sand. In contrast, the concrete made only of RBFA showed slump values from 23 mm to 43 mm. Typically, when the water-to-cement ratio is lower, the compressive strength obtained is higher. However, the slump value is lower compared to the cases with a higher water-to-cement ratio.

For this investigation, the tensile strength of concrete was assessed only at 28-days. It has been observed that when the replacement ratio of recycled fine aggregate (RBFA) rises, the tensile strength of concrete drops for the recycled brick fine aggregates. Replacing natural sand with recycled fine aggregate does not significantly decrease the Young's modulus of concrete [54].

3.5. Washed Waste Fine Aggregate (WWF) Concrete

According to Figure 5, when WWF is used as a replacement for natural sand, it enhances the compressive strength of concrete compared to the control case where no WWF is used. The concrete mixture, which utilized CEM Type I cement and WWF-20% as a substitute for sand, exhibited the highest compressive strength of 37.01 MPa. The compressive strength significantly improved by more than 25% compared to the corresponding control case utilizing 100% natural sand. However, the increased rates in compressive strength for alternative cement varieties were comparatively lower than those of CEM Type I, varying from 1% to 17%. The strength of CEM Type II A-M only increased by 1%. For cement with a fly ash content of 65%, the compressive strength exhibited a 17% increase compared to the control case. The compressive strength is enhanced by 13% when the slag content is 50% compared to the control case. The smaller particles in WWF, along with its elevated alkalinity and greater absorption capacity, enhance strength by filling empty spaces, speeding up the process of hydration reactions, and facilitating the hydration of cement particles through internal curing.

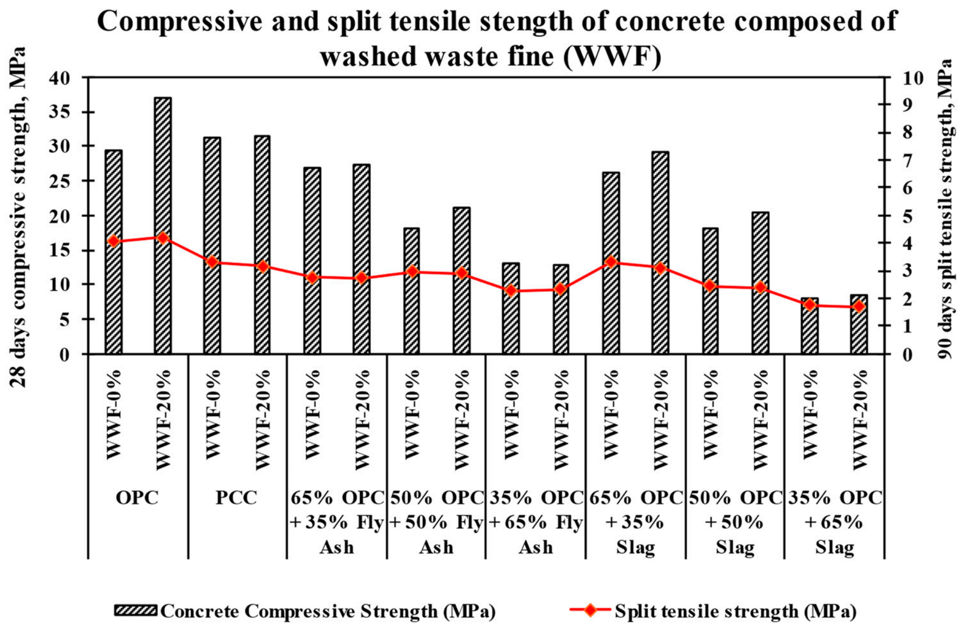


Figure 5. Washed Waste Fine: Compressive Strength and Split Tensile Strength.

Nevertheless, the extent to which the inclusion of WWF enhances strength differs across different concrete compositions. The difference in cement content can account for this observation. The pure clinker-based cement (CEM Type I) had a significantly improved strength, attributed to the internal curing. Compared to pure clinker-based cement, the strength growth was less when pozzolans were present. A separate investigation also showed similar findings [61].

Based on the 90-day tensile strength data for various concrete mixtures with and without WWF, it can be observed that the mixture, including OPC and 20% WWF, exhibits the maximum tensile strength of 4.19 MPa, similar to the compressive strength of concrete. The data also suggest that replacing 20% of sand with WWF did not substantially impact the tensile strength of concrete. The tensile strength of concrete, regardless of the type of cement used, was almost the same when comparing the cases with and without WWF.

When comparing WWF to natural sand, it was observed that WWF is a similarly porous material. However, replacing 20% of sand with WWF did not decrease the tensile strength of concrete.

4. Circular Economy

The circular economy is related to Sustainable Development Goal 12 (SDG 12) [62], which ensures sustainable consumption and production; both are significant for preserving natural resources and minimizing environmental effects [63]. Figure 6 demonstrates a practical method for achieving this objective by utilizing alternative fine aggregates instead of river sand in construction.

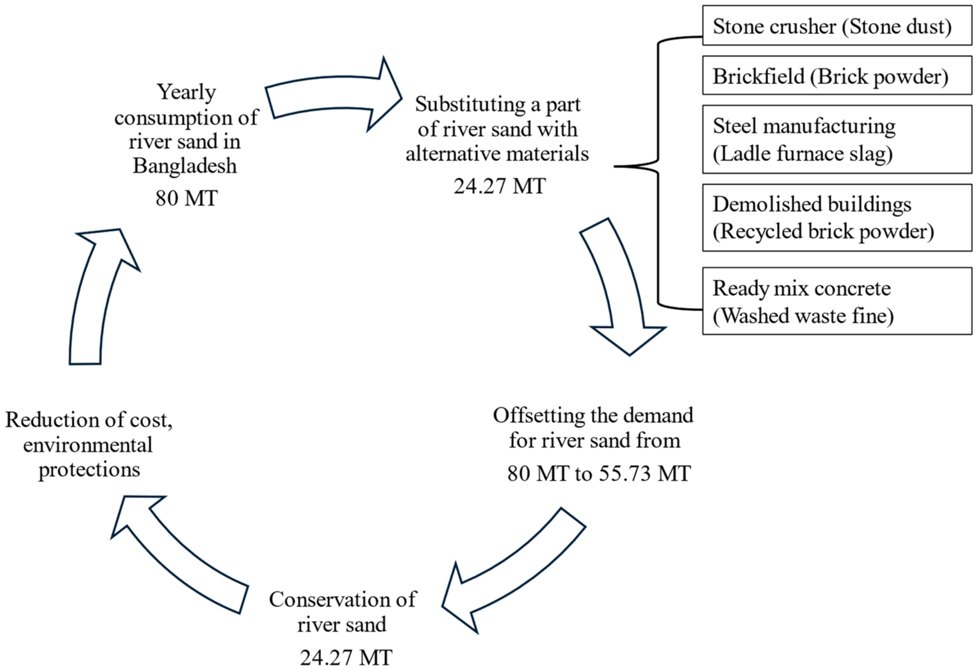


Figure 6. Circular Economy in Relation to Fine Aggregate Production and Use in Bangladesh.

Keeping in mind the target of attaining SDG12, material flow analysis (MFA) related to fine aggregate was conducted from Bangladesh's perspective. In Bangladesh, around 80 million tons of fine aggregate are needed annually. This is mainly collected from natural rivers, leading to harmful environmental impacts.

Figure 7 presents a comprehensive investigation of the material flow of alternate fine aggregates compared to natural river sand. It demonstrates that using alternative resources can offset the demand for natural river sand by up to 30% with these alternative sources of fine aggregate.

Bangladesh primarily relies on crushed stone imports for its construction industry, with an estimated demand of around seventy million tons annually [64]; 5% of this can be used as SFA. According to investigations by the Asian Development Bank (ADB), the country's yearly brick production is around 22.71 billion pieces [65], 10% of which could potentially be used as BFA. Several news reports, including one from The Daily Star, state that Bangladesh can produce about 9 million tons of steel yearly [66]. Ladle-refined furnace slag can be collected from these steel industries, and up to 15% of the slag (LFS) can be used as fine aggregate. In 1990, the country's cement production was nearly 1 million tons [67]. Most of those buildings now need to be demolished, and around 10.29 MT of RBFA could be collected from old structures; this amount will be increased due to the gradually increasing number of old buildings undergoing demolition. Annually, 12 million cubic feet of ready-mix concrete is produced in the country; 20% of these wasted products can be utilized as WWF. Using these alternative materials, around 30% of natural river sand could be conserved.

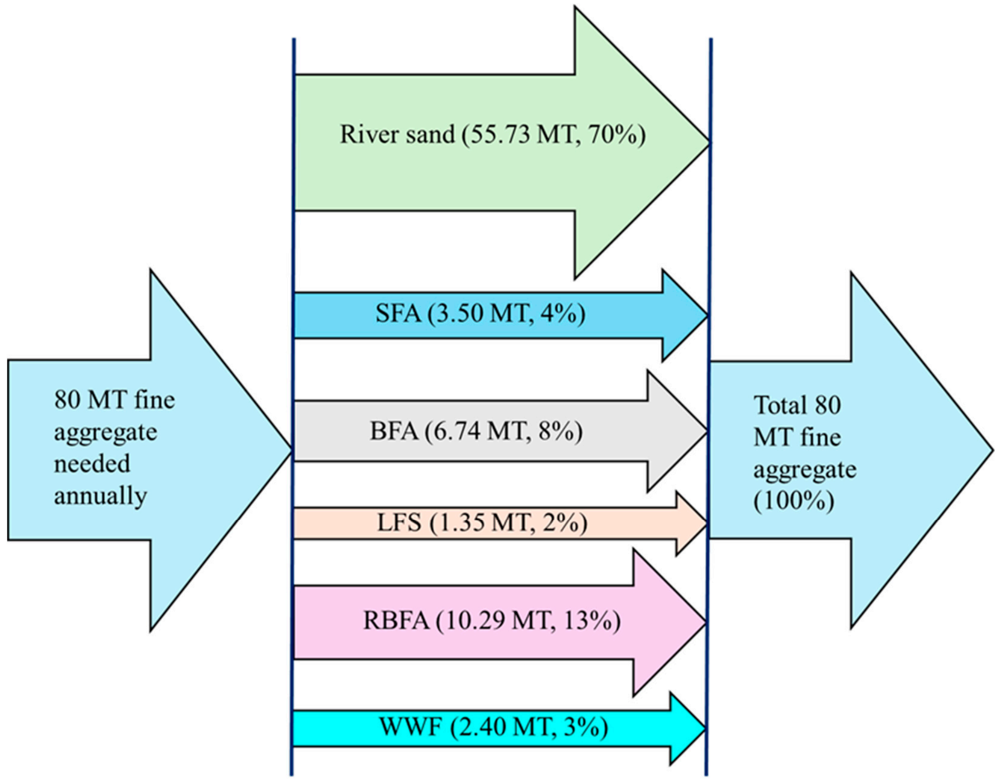


Figure 7. Material Flow Analysis.

5. Conclusions

The experimental investigation assessed the viability of substituting natural sand with SFA, BFA, LFS, RBFA, and WWF. Based on the findings, the following conclusions may be made:

1. To achieve the optimum mechanical properties of concrete, natural sand can be replaced by 30% of BFA or SFA. In the case of LFS, the optimum replacement of natural river sand was 20%. Concrete can be produced by 100% replacement of RBFA and 20% replacement of WWF without sacrificing its compressive strength.
2. Utilizing these alternative fine aggregates can reduce the consumption of natural river sand by 30%.
3. These alternative materials, fine aggregates, can be utilized to ensure the circular economy, i.e., to attain the goals of SDG12 (Ensure sustainable consumption and production patterns).
4. Future research may investigate other alternative waste materials available in Bangladesh and their mechanical and durability studies for replacing concrete fine aggregate with such alternatives.

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