ALTERNATIVE COARSE AGGREGATE AND SUPPLEMENTARY CEMENTITIOUS MATERIALS FOR SUSTAINABLE CONCRETE STRUCTURES: A REVIEW ON CHARACTERIZATION AND PROPERTIES

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ABSTRACT

The most popular building material in the world, concrete, contributes significantly to greenhouse gas emissions during production. Concrete is the second most consumed substance in the world, following water. In traditional concrete, the natural particles take up around 65-70% of the volume. Concrete is considered a sustainable material due to its limited energy consumption, customized production process with minimal waste, utilization of abundant resources, high thermal mass, ability to incorporate recycled materials and full recyclability. The primary objective of this research is to replace natural aggregates with sustainable alternatives such as coconut shells, oil palm shells, recycled concrete aggregates (RCA), recycled glass, and recycled ceramic tiles. By utilising these materials, we aim to conserve natural resources for future generations while producing high-quality concrete. Additionally, supplementary cementitious materials (SCMs) will be incorporated to enhance the performance of the concrete. Alternative coarse aggregate and supplementary cementitious materials (SCMs) can be used to create environmentally friendly concrete constructions. This review aims to provide a concise summary of the prior research on the application of several alternative coarse aggregates and SCMs. Recycled glass, recycled tile, and recycled concrete aggregate are all suitable substitutes for coarse aggregate. Fly ash, blast furnace slag and, silica fume etc are examples of SCMs. As a result, the information in this paper will be crucial and beneficial for researchers looking for substitute coarse aggregate and additional cementing ingredients in the field of advanced concrete technology. This review's conclusion highlights the importance of alternate coarse aggregates and SCMs in enhancing the sustainability of concrete structures. This analysis provides valuable information for scientists, engineers, and legislators who are striving to create a more sustainable future for the construction sector. It thoroughly examines the traits and qualities of these individuals. Overall, the analysis demonstrates that a wide variety of substitute coarse aggregate and SCMs can make environmentally friendly and more effective sustainable concrete structures.

Keywords: *Sustainable materials, Alternative coarse aggregate, Supplementary Cementitious Materials (SCMs), Recycled concrete, Environment friendly concrete.*

1. INTRODUCTION

Concrete is the second most often used material globally, after water. It has an annual output rate of around two cubic meters per person. The widespread appeal of concrete can be attributed to its cost-effectiveness, ease of manufacturing, adaptability, and potential for local production and utilization (Duchesne, 2021). Sustainability, as defined by the World Commission on Environment and Development, refers to the concept of satisfying the current requirements while ensuring that future generations can also fulfil their own needs without any hindrance. Sustainability refers to the concept of prioritizing the welfare of our planet while ensuring ongoing growth and human progress (Naik & Moriconi, n.d.). Sustainability, as defined by the World Commission on Environment and Development, refers to the concept of fulfilling the requirements of the current generation without jeopardizing the capacity of future generations to fulfil their own needs. Sustainability is the concept of prioritizing the welfare of our planet while ensuring ongoing growth and human progress (Naik et al. 2005).

Portland cement is the predominant binding agent utilized in the production of concrete. Portland cement is produced through the high-temperature calcination (at temperatures exceeding 1450 °C) of a mostly limestone (CaCO3) combination. Nevertheless, Portland cement systems have certain disadvantages, such as their negative impact on the environment and lack of sustainability (Kosmatka & Wilson, 2011). In order to mitigate the effects of climate change, it is imperative to decrease carbon emissions and decrease the concentration of CO2 in the atmosphere (Fernández-Jiménez et al., 2005). Substituting Portland cement with Supplementary Cementitious Materials (SCMs) diminishes waste, enhances the properties of the concrete, and extends the durability of constructions. Utilizing SCMs is a highly effective method for managing the expansion of air pollutant emissions from cement plants, encompassing both gases and particulate matter. Various forms of SCMs are available, including classic ones like silica fume, fly ash, granulated blast furnace slag (Thomas et al., 2019).

The utilization of waste materials as construction materials has several benefits, such as cost reduction, energy savings, and environmental safety. Aggregates are non-reactive, granular substances utilized as cohesive agents in concrete (Cui et al., 2015). Construction and Demolition (C&D) wastes can be utilized as aggregates in concrete to address the limited availability of aggregates. Recycled Coarse Aggregate (RCA), Recycled Glass Aggregate, and Recycled tile aggregates (RTA) are commonly utilized in construction. They can be employed in either coarse or fine form as a filler medium (Yong Ho et al., 2013a). The use of finer or coarser materials as a partial or total substitute for Natural Coarse Aggregates (NCA) has ushered in a new age in concrete (Jagan et al., 2020).

2. SUSTAINABILITY

Sustainability refers to the concept of satisfying the current demands while ensuring that future generations can also fulfil their own requirements without any compromise. This idea incorporates environmental, social, and economic elements. Complete geographic areas are experiencing a depletion of limestone reserves for cement production. Urban centres are facing a depletion of aggregate resources required for concrete production (Corinaldesi et al., 2002).

A sustainable concrete structure is one that is built to minimize its overall societal impact throughout its full life cycle, including its use. Designing for sustainability entails considering the complete immediate and long-term ramifications of the societal influence in the design process. Hence, the primary concern is the durability (Monconi1 et al., 2003). The research has also demonstrated that concrete produced from agricultural wastes has superior thermal qualities. This can lead to the acquisition of sustainability points in the "Optimize Energy Performance" credit of the LEED grading system, namely in the energy and atmosphere category. Therefore, including agricultural and industrial waste as aggregate in concrete manufacturing can enhance the environmental sustainability of the material and the structure it is utilized in (Horst, 2009).

3. SUSTAINABLE SOLUTIONS WITH CONCRETE

Concrete is a tough and long-lasting construction material with little negative effects on the environment. It serves as the essential foundation for designing buildings and infrastructure that may guide future generations towards a sustainable future (Naik & Moriconi, n.d.). The advantages of concrete construction are numerous. Concrete buildings, for instance, require less maintenance and energy compared to other materials. Concrete roadways reduce fuel consumption by facilitating the transportation of heavy loaded trucks. Insulating concrete homes can significantly decrease energy consumption by 40% or even more. Furthermore, concrete is effective in containing agricultural waste, as it helps to reduce odour and prevent groundwater contamination (Naik & Moriconi, n.d.). In order to contribute to the sustainable growth of the concrete industry in the 21st century, it is imperative for the industry to demonstrate leadership and determination. This can be achieved by embracing innovative technologies that effectively limit the emission of greenhouse gases. By doing so, the industry will play a significant role in achieving the aims and objectives (Bastos et al., 2016).

4. AGGREGATE ALTERNATIVES

Concrete mixtures consist mostly of cement, water, and particles. The concrete industry is indisputably the most significant consumer of natural resources globally among all manufacturing businesses. In addition, the extraction, refining, and transportation of significant amounts of raw materials used in cement production, as well as the production of concrete aggregates, result in substantial energy consumption and have detrimental effects on the ecosystems of riverbeds and forested regions (Naik & Moriconi, n.d.). Currently, the South European countries (Spain, Italy, Greece, and Greece) have a low rate of recycling for their Construction and Demolition Waste (C&DW). Their abundant and high-quality natural resources adequately fulfil the need for construction materials at a reasonable price, which consequently hinders the growth of the market for recycled materials to emerge (Naik & Moriconi, n.d.).

4.1 Recycled Coarse Aggregate (RCA)

Utilising larger recycled coarse aggregates (RCA) as a partial or full replacement for natural coarse aggregates (NCA) has introduced a new era in concrete referred to as "Recycled Aggregate Concrete (RAC)". Several research studies have investigated the features of recycled coarse aggregate (RCA), including its mechanical properties and the durability of raw recycled aggregate concrete (RAC) (Yong Ho et al., 2013b).

The amount of adhering mortar is contingent upon the size of the coarse aggregate. The amount of mortar adhered to the surface of Recycled Coarse Aggregate (RCA) will increase when the size of the Coarse Aggregate (CA) is smaller (Kong et al., 2010). The shape and texture of RCA are greatly impacted by the type of crusher used and the technique of manufacture of RCA (Kong et al., 2010). Moreover, the quality of the recycled coarse aggregate (RCA) is mostly determined by the quality of the original concrete. Specifically, using high strength concrete leads to the production of RCA with superior characteristics (Jagan et al., 2020). The table 1 provides a comprehensive analysis of the physical features of RCA and NCA.

Table 1: Comparison of physical properties between RCA and NCA (Safiuddin et al., 2013)

Properties	RCA	NCA
Specific Gravity (SSD)	2.1-2.5	2.4-2.9
Water Absorption (wt.%)	3-12	.5-4
Bulk Density (kg/m^3)	1200-1425	1450-1750
Crushing Value (%)	20-30	14-22
Abrasion Value (wt.%)	20-45	15-30

With the exception of water absorption, the physical parameters of RCA generally conform to the BIS limit specification. The water absorption of recycled concrete aggregate (RCA) exhibits an approximate

96% increase in comparison to natural concrete aggregate (NCA) within a 24-hour period. In recycled aggregate concrete, there is a decrease in mechanical strength, and this decrease is closely related to the quality of the recycled aggregate. However, when the recycled aggregates are made up of demolished concrete that has the same or higher strength as the new concrete they will be used in, this decrease in strength is completely eliminated (Behera et al., 2014).

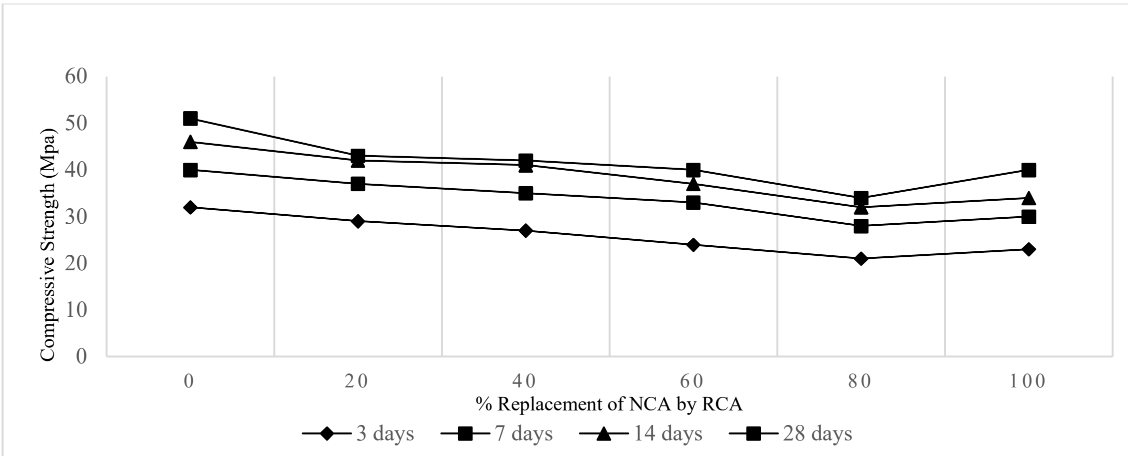
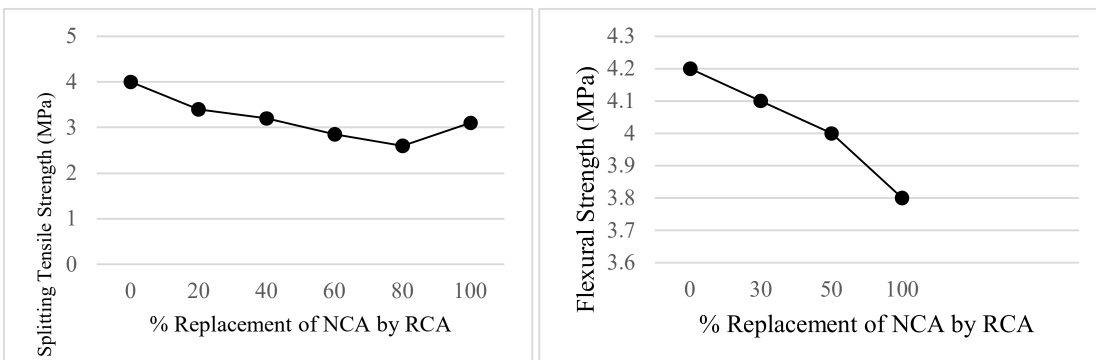


Figure 1: Compressive strength test results



(a) (b)

Figure 2: (a) Splitting Tensile test results; (b) Flexural Strength test results

4.2 Recycled Glass Aggregate (RGA)

Glass and glass fibres are utilized in concrete for multiple purposes, such as controlling cracks, preventing cracks from merging, and altering the material's behaviour by the bridging of fibres over the cracks (Shahabi et al. 2007). The physical features of RGA is presented in table 2.

Table.2: Characteristics of physical properties between RGA (Prasad & Rathish Kumar, 2007)

Properties	RGA
Specific Gravity	2.4-2.6
Water Absorption	1.65-13.1
Bulk Density (kg/m^3)	500-1200
Crushing Value (%)	4.5-15.2

The experiment demonstrates the changes in the compressive and split tensile strength of concrete specimens after being cured in water for different durations (3, 7, 14, 28, 42, and 90 days), while waste glass replaces the natural fine and coarse materials. As anticipated, there was an increase in strength. The findings demonstrate a decrease in compressive strength as the proportion of waste glass aggregate increases, ranging from 50% to 100%, replacing the natural aggregate. The compressive strength increased when 25% of the natural aggregate was replaced with waste glass, as compared to the control mix. After 28 days, the mixture containing 25% waste glass successfully reached the desired strength of approximately 20 MPa (Olofinnade et al., 2016).

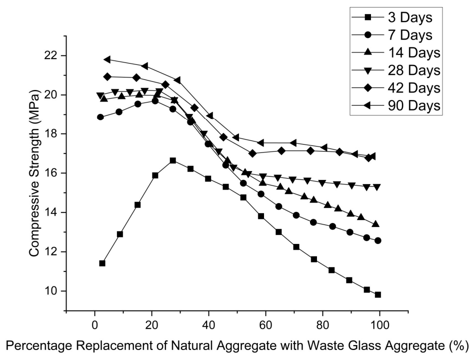


Figure 3: Result of Compressive Strength

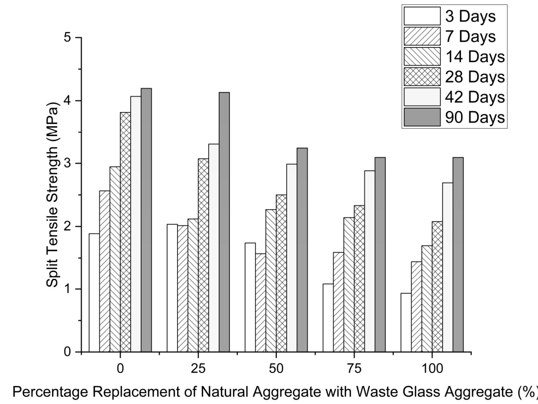


Figure 4: Result of Split Tensile Strength

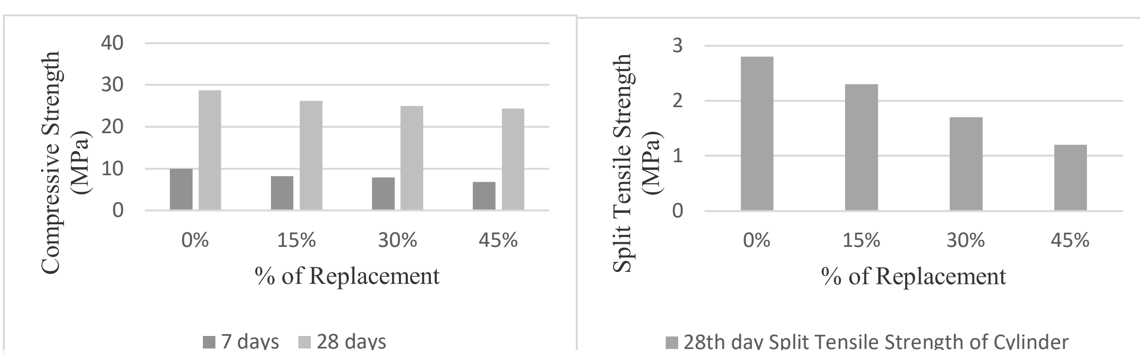
4.3 Waste Ceramic Tiles:

Ceramic tile aggregates possess a high specific gravity and are characterized by a rough surface on one side and a smooth surface on the other. Additionally, they are lighter in weight compared to traditional stone aggregates. Utilizing ceramic tile aggregate in concrete offers both cost-effectiveness and environmental benefits. The physical features analysis of CTA is presented in table 3.

Table.3: Comparison of physical properties between CTA (Sekar, n.d.)

Properties	**CTA**
Specific Gravity	2.16-2.61
Impact Value (%)	20-45
Crushing Value (%)	12-32
Abrasion Value (%)	15-40

The mechanical characteristics of ceramic aggregate closely resemble those of natural aggregate; however, they are not identical. The water absorption, crushing value, and impact value of the material are more than those of natural coarse aggregate, while its specific gravity is lower, measuring 2.24 g/cm3. The research on the strength properties of concrete made with waste materials revealed that concrete built with waste ceramic tile aggregate exhibited comparable strength in compression, split tensile, and flexure to conventional concrete (Sekar, n.d.).



(a) (b)

Figure 5: (a) 7 & 28 days Compressive and; (b) 28 days Split Tensile Strength test result

5 PORTLAND CEMENT ALTERNATIVES

Portland cement is considered to have a limited level of environmental friendliness. In order to adhere to engineering best practices, it is imperative to minimize the utilization of concrete and instead prioritize the incorporation of blended cements, particularly those enhanced with chemical admixtures (Naik & Moriconi, n.d.). Blended cement is produced by incorporating fly ash, blast furnace slag, or silica fume into the cement mix during the grinding phase of cement manufacturing. The advantages include higher production capacity, reduced carbon dioxide emissions, lower fuel consumption, and precise control over the quality of supplemental cementitious materials (Naik & Moriconi, n.d.).

5.1 Application using Fly Ash (FA)

Fly ash (FA) is a residual substance generated by coal-fired power plants in the industrial sector. The FA used in the study has been classified as class C & F, in accordance with the specifications outlined in ASTM C618–19. The utilization of a significant amount of fly ash (FA) at a high volume (60% of the binder weight) in cement paste/mortar has a notable impact on the physical and chemical characteristics of the cementitious system, leading to alterations in its microstructure. According to (Amin & Abdelsalam, 2019) the substitution of cement with FA results in an elevation of the water-to-cement ratio, leading to diminished early age strength. According to (Amin & Abdelsalam, 2019), alkali-activated FA mortars exhibit greater durability compared to typical Portland cement mortars in experimental settings, irrespective of the specific activator employed. The physical and chemical characteristics of fly ash are presented in Table 4.

Table.4: Physical and chemical properties of Fly Ash (Comesa And Sadc Harminized)

Physical Properties		
Properties	**FA**	
Specific Gravity (g/cm^3)	1.9 – 2.96	
Bulk Density (g/cm^3)	0.7 – 1.1	
Water Absorption (%)	0.5 - 15	
Abrasion Value (%)	6.4 – 12.2	
Crushing Value (%)	4.5 – 15.2	
Impact Value (%)	25 – 45	
Chemical Properties		
Elements Oxides	**Range of Element Oxides (%)**	
	Class F	**Class C**
SiO_2	37.0 – 62.1	11.8 – 46.4
Al_2O_3	16.6 – 35.6	2.6 – 20.5
Fe_2O_3	2.6 – 21.2	1.4 – 15.6
CaO	0.5 – 14.0	15.1 – 54.8
MgO	0.3 – 5.2	0.1 – 6.7
SO_3	0.02 – 4.7	1.4 – 12.9
Na_2O	0.1 – 3.6	0.2 – 2.8
K_2O	0.1 – 4.1	0.3 – 9.3
TiO_2	0.5 – 2.6	0.6 – 1.0
P_2O_5	0.1 – 1.7	0.2 – 0.4
MnO	0.03 – 0.1	0.03 – 0.2
LOI	0.3 – 32.8	0.3 – 11.7

The majority of "Class F" is produced from the combustion of anthracite or bituminous coal that contains concentrations of SiO2, Al2O3, and Fe2O3 exceeding 70%. The production of "Class C" FA involves the combustion of lignite or sub-bituminous coal, which contains around 50% to 70% of the specified compounds. The incorporation of FA as a substitute for cement in concrete mixtures resulted in enhancements in the modulus of elasticity, with varying degrees of improvement seen. a replacement ratio of 20% of fine aggregate (FA) is considered optimal for each cement content (Amin & Abdelsalam, 2019). An analysis of mechanical performance indicates that the presence of fly ash reduces the compressive strength. The strength diminishes considerably as the replacement ratios increase. When the replacement ratio reaches 40%, the strength of the mix is reduced by 60% compared to the control mix. With an increase in the amount of fly ash, there is a decrease in the splitting tensile strength. Data exhibits variations. The strength experiences a significant decline at a replacement ratio of 20%, but somewhat recovers at a replacement ratio of 30%. As the amount of fly ash increases, the flexural strength decreases. The decrease in strength is smaller compared to the decrease in compressive strength (Li et al., 2022).

Table 5: Mechanical performance with Fly Ash % variation (Berndt, 2009)

Test	**Replacement Ratio (%)**	**Strength in MPa**
Compressive Strength Test	0	33.4
	10	29.7
	15	23.3
	20	25.2
	30	22.2
	40	13.5
Splitting Tensile Strength Test	0	1.72
	10	1.58
	15	1.58
	20	0.89
	30	1.21
	40	0.89
Flexural Strength Test	0	1.82
	10	2.19
	15	1.62
	20	1.53
	30	1.62
	40	1.04

5.2 Application using Blast Furnace Slag

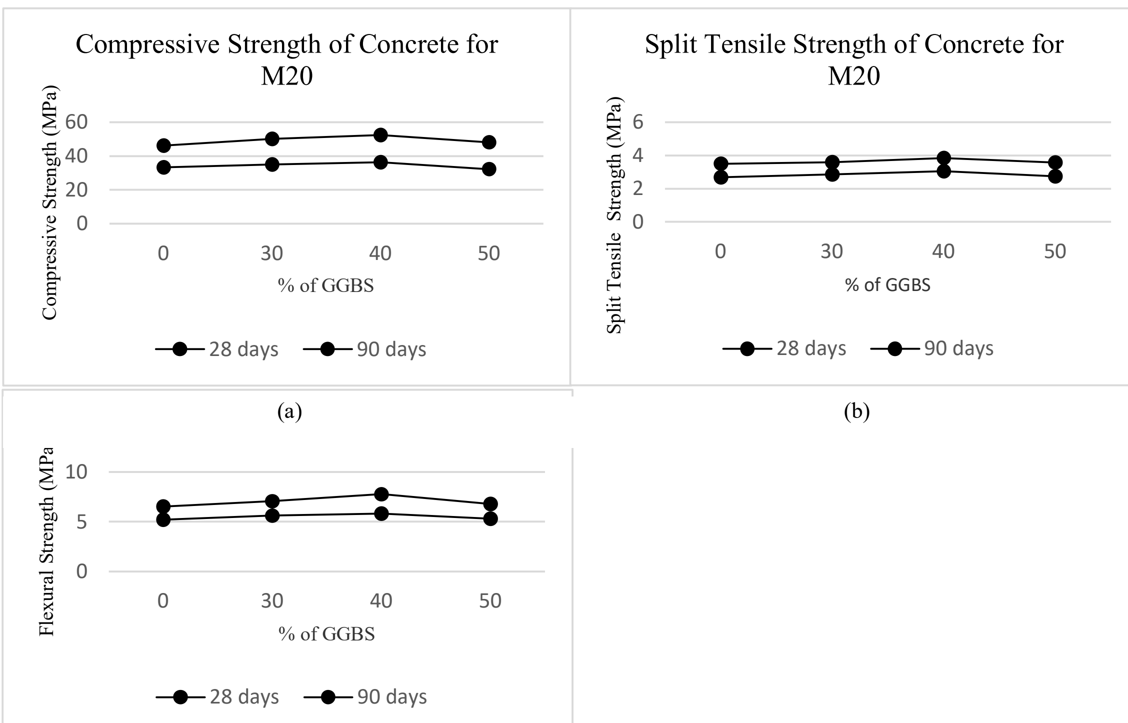
Blast furnace slag (BFS) is a non-metallic product composed primarily of calcium silicates and alumina silicates, which forms alongside iron in a molten state during the operation of a blast furnace. This definition is provided by the ASTM C 125-16 (2016) standard (Kumar Karri et al., 2015). GBFS has the potential to serve as a viable substitute for conventional cement, with a range of replacement ratios spanning from 30% to 85% (Kumar Karri et al., 2015). The chemical and physical characteristics of Blast Furnace Slag are presented in Table 6.

Table 6: Chemical and physical properties of Blast Furnace Slag (Berndt, 2009)

Physical		**Chemical**	
Properties	**Value Range**	**Properties**	**Range**
Specific Gravity (g/cm^3)	2.85-3.1	SiO_2	30-38%
Bulk Density (g/cm^3)	1-1.3	Al_2O_3	8-10%
Water Absorption (%)	0.5-8.3	CaO	30-50%
Loss of Ignition (%)	0.5-2	MgO	2-8%
Abrasion Value (%)	15-40	Fe_2O_3	0.5-2%
Crushing Value (%)	4.5-15.2%	MnO	0.5-2%

Impact Value (%)	20-45	TiO_2	0.5-1%
		S(Sulfur)	0.5-1%
		Loss of Ignition (%)	0.5-2%

Based on the conducted research, it was observed that the incorporation of 50% blast furnace slag in the natural aggregate mixes yielded favourable outcomes. More precisely, this composition demonstrated the highest level of strength compared to all the other examined mixtures, with measurements of 45.7 and 49.8 MPa at 28 and 84 days, respectively. The incorporation of 70% slag as a cement replacement led to a marginal decrease in strength when compared to concrete with 50% slag content. The inclusion of 50% and 70% slag in the natural aggregate mixes resulted in an increase in the splitting tensile strength (Berndt, 2009). The findings of the study revealed that the use of blast furnace slag as a 50% replacement for cement in concrete mixes yielded superior outcomes in terms of mechanical qualities and durability, regardless of whether natural or recycled concrete aggregate was utilized. The use of recycled concrete aggregate had little detrimental effects on the concrete's strength, particularly when used in conjunction with slag (Berndt, 2009).



(c)

Figure 6: (a) Compressive Strength Test; (b) Split Tensile Test and; (c) Flexural Strength test Results

5.3 Application using Silica Fume (SF):

Silica fume is a secondary material generated during the production of ferrosilicon alloys or silicon metal silicon metal. The process of manufacturing silica fume entails the reduction of quartz with a high level of purity (SiO2) within electric arc furnaces operating at temperatures over 2000°C (Samad & Shah, 2017). Silica fume is a finely powdered substance primarily composed of spherical particles with a diameter of 0.15 mm. According to (Samad & Shah, 2017), The average size of silica fume particles is roughly 100 times smaller than that of cement particles. Table 7 summarises the physical and chemical properties of Silica Fume.

Table 7: Physical and chemical properties of Silica Fume (Samad & Shah, 2017)

Physical Properties		Chemical Properties	
Properties	**FA**	**Properties**	**FA**
Specific Gravity (g/cm^3)	2.2 – 2.5	SiO_2	85 – 95%
Bulk Density (g/cm^3)	130 - 430	Al_2O_3	0.5 – 3%
Loose Bulk Density (g/cm^3)	200 - 600	Fe_2O_3	0.5 – 2%
Compacted Bulk Density (g/cm^3)	1300 – 1400	CaO	1 – 3%
Surface Area (m^2/kg)	15000 - 30000	MgO	0.5 – 2%
Mean Particle Size (µm)	0.1 – 0.2	Na_2O & K_2O	0.5 – 2%
Fineness	95%<1µm	SO_3	0.5 – 1%
Loss of Ignition (%)	1.70	LOI	0.5 – 3%

Based on empirical studies, it has been observed that the typical proportion of silica fume incorporated in concrete is generally below 8% of the cement content. However, it is worth noting that in certain cases, this proportion can be increased to 12.5% or even higher. The standards BS EN 13263-1 (2005) and BS EN 13263-2 (2005) are relevant for the use of silica fume in concrete, as mentioned by (Samad and Shah 2017). Silica fume exhibits a high level of reactivity as a pozzolan due to its distinct chemical and physical characteristics. The incorporation of silica fume in concrete has been found to significantly enhance its compressive strength and durability. The addition of silica fume to concrete has been found to reduce its permeability and inhibit the penetration of chloride ions into the reinforcement. Additionally, it has been observed that the incorporation of silica fume in concrete enhances its electrical resistance to corrosion (Samad & Shah, 2017)

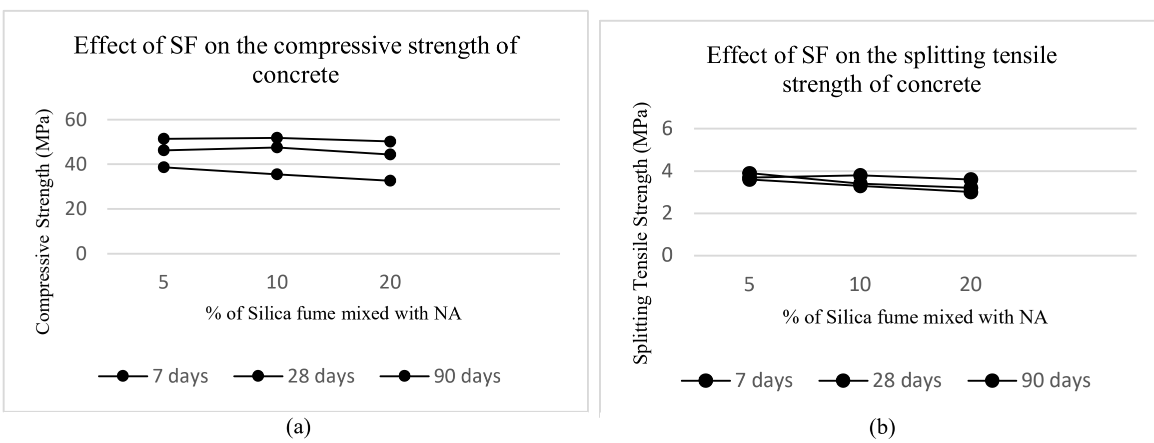


Figure 7: (a) Compressive Strength Test and; (b) Split Tensile Test Results

Silica fume, a common cementitious ingredient, was added to cement at 5%, 10%, and 20% in this investigation. The study examined how these mixtures affect compressive strength at 7, 28, and 90 days after cure. The compressive strength test showed intriguing patterns. As silica fume content increased during the 7-day curing period, compressive strength increased: 38.7 MPa (5%), 46.2 MPa (10%), and 51.4 MPa (20%). After 28 days, the compressive strength revealed a more complex correlation, with 5% and 20% silica fume concentrations having lower values than 10% (35.5 MPa, 44.7 MPa, and 47.5 MPa, respectively). After 90 days, compressive strength increased to 32.6 MPa (5% silica fume), 44.7 MPa (10%), and 50.8 MPa (20%). These findings emphasize the importance of considering silica fume proportion and curing period to maximize cementitious material compressive strength in real-world circumstances (Çakır & Sofyanlı, 2015).

An experiment was conducted to assess the splitting tensile strength of concrete using different proportions of silica fume, namely 5%, 10%, and 20%. Concrete samples were cured for 7, 28, and 90 days. Tensile strength increased with silica fume over 7 days, reaching 3.6, 3.9, and 3.0 MPa. After 28 days, 5% silica fume increased 3.9 MPa, while 10% and 20% decreased 3.4 and 3.2 MPa, respectively. The results highlight the slight effect of silica fume on splitting tensile strength and the importance of amounts for appropriate concrete mechanical properties (Çakır & Sofyanlı, 2015).

6. CONCLUSION

Given the global population growth, it is imperative to prioritize sustainable development, with the concrete sector playing a significant role in achieving this objective. One such strategy is the utilization of by-products and agricultural residues within the composition of concrete. This study provides a comprehensive examination of the diverse physical characteristics exhibited by alternate coarse aggregates and supplementary cementitious materials (SCMs), as well as their extent of incorporation in concrete.

- The characteristics of recycled aggregate concrete (RAC) are significantly impacted by various factors, including the quality of recycled coarse aggregate (RCA), recycled tiles aggregate (RTA), and recycled glass aggregate (RGA). Achieving appropriate surface saturation of RCA, RTA, and RGA within concrete represents an advantageous approach to mitigate water absorption during the cement hydration process, hence optimizing the overall performance of the concrete mixture.
- The utilization of solid waste as a substitute for conventional aggregate in concrete has a substantial impact on cost effectiveness, energy conservation, and the reduction of environmental consequences in the construction sector. This is due to the fact that aggregate constitutes approximately 60-80% of the total volume of concrete.
- The utilization of supplementary cementitious materials (SCMs) in concrete production has the potential to enhance the environmental equilibrium of concrete by substituting a portion of the clinker. There is currently a significant level of interest in the utilization of novel and sophisticated characterization methodologies for the evaluation of Additive Subtractive Combination Manufacturing (ASCM).
- Different supplemental cementitious materials (SCMs), such as Fly ash, Silica fumes, Blast Furnace Slag, and natural pozzolans (RHA), have varying effects on the properties of hardened concrete. The results include the enhancement of strength, resistance to wear and tear, resistance to freezing and thawing as well as deicer damage, reduction in drying shrinkage and creep, permeability, prevention of alkali-silica reaction, resistance to chemicals, and protection against carbonation.

Additional research is required in order to produce a universally accepted specification and a globally applicable mix design approach for supplementary cementitious materials (SCMs). In light of the prevailing standards for sustainable infrastructure, the utilization of alternative aggregates and cementitious materials in the production of concrete holds potential for fostering environmental friendliness within the concrete industry. Hence, the advancement of current knowledge and the exploration of additional viable alternatives for concrete production will make a significant contribution to the industry's environmental sustainability.

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