Kathmandu University Journal of Science, Engineering and Technology, Vol. 18, No. 2, December 2024

Kathmandu University
Journal of Science, Engineering and Technology

An overview of incorporating steel mill scale in the production of sustainable concrete

Onuegbu. O. Ugwu[a], Thaddeus T. Tarzomon[b], and Terlumun Adagba*[c]

[a]Civil Engineering Department, Alex Ekwueme Federal University Ndufu-Alike Ikwo, Ebonyi State Nigeria.
[b]Civil Engineering Department, University of Nigeria Nsukka, Enugu State, Nigeria.
[c]Civil Engineering Department, Federal University Dutsin-Ma, Katsina State, Nigeria.

Abstract

The rise in construction and infrastructural development has severely impacted the level of natural source utilization employed in concrete production leading to an astronomical increase in the cost of construction, scarcity of materials and other environmental concerns. The need to preserve our natural resources while mitigating the cost of concrete production has therefore triggered the search for alternative concrete producing materials. In this review, a critical look at the potential of incorporating steel mill scale in concrete production has been examined. Literature analysed confirmed it's suitability as waste that can be employed in the production of sustainable concrete. It's pulverisation makes it suitable for cement replacement showing that it falls into the class C fly ash of low pozzolanity. The optimal level of steel mill scale replacement is between 10%-30%, although at 100% replacement steel mill scale concrete has been reported to outperform control specimens. Steel mill scale incorporation produces concrete with high specific gravity and consequently high density, improved mechanical, water absorption and durability properties while negatively impacting the workability of concrete. For a wider application, much research is required so as to raise awareness among construction professionals.

Keywords: Steel mill scale; Sustainable concrete; Durability; Aggregates; Concrete properties.

1. Introduction

Concrete is the most widely used construction material in the world which gives it this popularity that comes at an immense environmental cost as billions of tons of natural materials to be used in concrete are mined and processed each year thereby leaving a substantial mark on the environment [1]. Concrete, a major component of modern infrastructural development consists of binding materials, natural aggregates - sand, gravel, and crushed rock-, water and admixtures [2, 3]. However, with the ever-increasing demands of construction, natural aggregates which are not readily replaceable and are formed over geological timescales are been depleted rapidly.

From the displacement of wildlife, fragmentation of habitats and destruction of ecosystems, the acquisition of natural aggregates can also cause other environmental issues such as air pollution, contamination of water sources from quarry runoff, noise generation, disruption of natural drainage patterns as well as impacting the aesthetics of our landscape by leaving behind large pits from quarrying. Hence, the need for sustainable alternatives in construction as replacement materials.

Research has shown sufficiently, the suitability of applying such replacement materials, mostly wastes, obtained from either agricultural or industrial sources. The recycling of such by-products by way of introducing them in concrete production has proved beneficial in several ways. Volume reduction of such wastes which alleviates the pressures on waste management systems, resource conservation by lowering the demand for virgin materials, cut down of greenhouse gas emissions hence combating climate change, utilizing less energy compared to energy required to produce new materials and curtailing environmental contamination are some of the environmental benefits this sustainable practice offers.

Economic benefits include saving costs required for waste disposal, generating revenue from re-processed and sold materials while enhancing market competitiveness through sustainable environmental practices while social benefits such as job creating opportunities from the collection, processing and sales of these wastes, an improved community health by mitigating risks associated with improper waste disposal and an improved organisational corporate social responsibility profile by organisations engaged in this sustainable practice. Several researches have also reported that the use of waste in concrete is beneficial and effective [2, 4, 5]. These benefits emphasize therefore, the need for sustainable alternatives in construction as replacement materials. This is where steel mill scale, one waste material yet to be extensively tested emerges as a potential replacement in the production of concrete [1]. This review article delves into the research surrounding the use of steel mill scale in concrete, with a particular focus on its potential to replace aggregates for sustainable concrete production. This will add to the existing body of knowledge on the suitability of steel mill scale as an alternative in the production of sustainable concrete and more eco-friendly construction practices.

2. The steel mill scale

2.1. Overview of the steel mill scale

Mill scale is one of the potential iron bearing by-product from hot rolling mill operations [6, 7]. Mill scale is a flaky hazardous

*Corresponding author. Email: adagbat@gmail.com

Figure 1: The raw steel mill scale. Source: [10].

Figure 2: Collection of Steel Mill Scale. Source: [11].

solid waste formed on the steel's surface during the steel manufacturing processes [1, 8]. The rolling process in steel manufacturing for which hot rolled ingots or billets is heated to a temperature of around 800^{0}C to 1200^{o}C and shaped by rollers thereby generating undesired scales of oxidized iron on the surface of the hot steel [9].

It is estimated that a metric tonne of hot rolled steel produces an estimated 35-40 kg of mill scale [6], [12]. Globally, 13.5 million metric tons is generated annually [13]. Consequently, the quantity of steel mill scale generated is considered enormous owing to the steel produced globally.

Steel mill scale, depending on the steel making process and parameters like oxygen exposure and temperature, consists majorly of varying proportions of iron oxides such as Wustite (FeO), Magnetite (Fe_3O_4), Hematite (Fe_2O_3) [6]. Elements like manganese, silicon, and aluminum may also be present [14], [15]. The steel mill scale is relatively inert and resistant to further corrosion owing to the presence of iron oxides [16].

Typically, steel mill scale is a bluish-black coloured, flaky or scale-like material having a density and surface texture comparatively higher and rougher than natural aggregates used in concrete. It is one of the most valuable industrial wastes [17] and a good substitute for fine aggregates in the construction industry [18]. Fig. 1 and Fig. 2 show the raw steel mill scale and it's collection at a dump site.

2.2. Utilization methods of the steel mill scale

Traditionally, the major disposal method of steel mill scale is the landfills. However, additional volume of steel mill scale further places more strain on available land which is a limited resource. Moreover, landfilling of this waste has the potential of causing environmental hazards over time such as the leaching of iron oxides impacting the soil quality and groundwater resources [19].

The general modes of recycling steel mill scale within the industry is through sintering, cold bonded agglomeration, direct injection, direct reduction and smelting reduction [7]. Other approaches of direct reduction recycling of mill scale through "iron powder" synthesis, the hydrogen reduction and carbon monoxide of Mill scale have also been reported [10, 20, 21, 22, 23]. It's application in the removal of heavy metals and other contaminants in water has also been investigated [12, 24, 25, 26]. Fig. 3 shows the various use of steel mill scale.

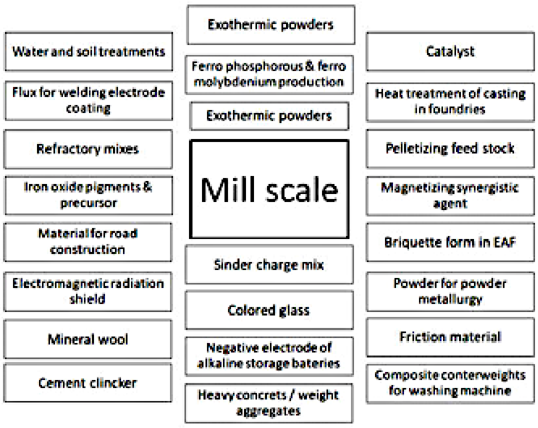

Figure 3: Different utilization methods of steel mill scale. Source: Nowacki et al. [22]

2.3. Processing and preparation

In order to achieve the desired size, steel mill scale undergoes either crushing or grinding. This process of crushing and/or grinding has been reported to have an effect on the physiochemical properties of steel mill scale [20]. Mill scale in it's untreated form usually contains contaminants such as dust, oil and grease which can negatively affect the bonding between mill scale and cement paste. It is therefore washed and cleaned to improve the surface chemistry for optimal adhesion [27]. Surface Modification may also be required by thermal or chemical treatment to modify the composition of the mill scale to promote better adhesion.

2.4. Benefits of the steel mill scale

Steel mill scales are finer particles than sand with high specific gravity. Hence, steel mill scale can be utilized to produce high density concrete [1, 19]. Other advantages are reduction in shrinkage, improved compressive strength, decreased water absorption and a dense microstructure [29]. The steel mill scale provides an opportunity for alternative material replacement with huge potentials for waste reduction and promoting a circular economy. It's utilization offers a means for reducing a significant amount of waste from landfills while maximizing resource utilization. Concrete utilization of this waste further promotes a circular economy in keeping materials in use for as long as possible, conserving the limited resources for future generations and enhancing sustainable construction practices which ensures the minimization of the environmental impact of the material's lifecycle.

3. Properties of the Steel Mill Scale

3.1. Physical properties

3.1.1. Particle size

Steel mill scale particles vary significantly in size, typically ranging from fine dust-like particles to larger flakes. The particle size distribution generally falls within the range of 0.1 mm to 10 mm with majority (nearly 90%) of the particles falling below 1mm [19].

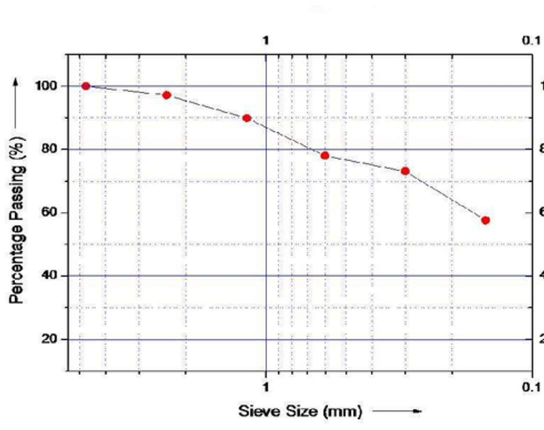

Figure 4: Particle size distribution curve for steel mill scale. Source: Murthy et al. [19]

While steel mill scale has different physical properties compared to natural sand, its particle size distribution is often similar enough. Consequently, by means of the particle size distribution, steel mill scale is suitable for sand replacement in concrete [30]. Table 1 shows a comparison of the particle size distribution for sand and steel mill scale. Fig. 4 shows the grading curve for the particle size distribution.

3.1.2. Specific gravity

Steel mill scale has a specific gravity that typically ranges between 4 to 6 (Table 2). Murthy et al. [19] in a study recorded a specific gravity of mill scale nearly two times that of sand. Steel mill scale was also reported to have a specific gravity approximately 1.87 times higher compared to the ordinary sand [32]. Higher values were also recorded in several other studies [30, 33]. Parvathikumar et al. [31] recorded a steel mill scale specific gravity of 4.10, a value much higher than the specific gravity of sand. This therefore explains the increase in density of concrete produced using steel mill scale.

3.1.3. Fineness modulus

Fineness modulus is a property that characterizes aggregate's particle size distribution and workability. Studies have shown that the particle size distribution of steel mill scale closely resembles that of natural sand. When steel mill scale is partially replaced for sand, the overall fineness modulus of the fine aggregate blend typically experiences only a slight change. Researchers have reported shifts in fineness modulus of less than 0.4 for even high replacement fractions. A study by [18] reported a resemblance of the fineness modulus of sand replaced concrete with that of natural aggregates having a range that was within 0.4 even for very high fractions of replacements.

3.2. Chemical composition of steel mill scale

The typical chemical composition of steel mill scale includes predominantly iron oxides (FeO, Fe_2O_3, Fe_3O_4) with iron content up to 70-75%. Minor components include SiO_2 (1-2%), CaO (<1%), MgO (<0.5%), Al_2O_3 (<1%), MnO (<1%), P (<0.1%), and S (<0.1%) [6]. It is therefore an inert material that can be used as a filler material as it exhibits no lime reactivity, hence not fit for use as binder but as aggregate replacements in concrete [16]. A study by Oyelade et al. [36] however indicated that pulverized steel mill scale (PSMS) had low CaO but higher silicates with the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ as 53.91%, hence PSMS posses low pozolanity which makes it an equivalent of a class C fly ash. This infers that pulverized steel mill scale can be incorporated to replace cement as a binder in concrete. Table 3 shows some of the chemical properties. Fig. 5 shows the XRD pattern of the mill scale.

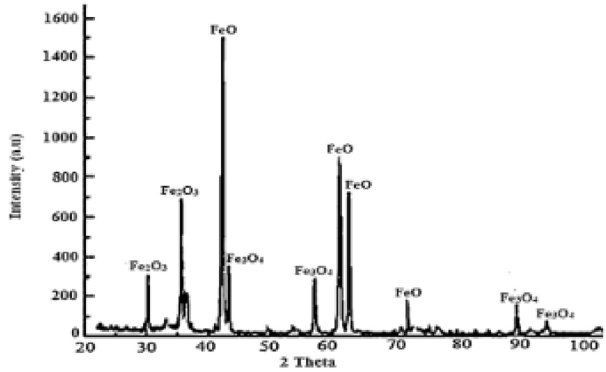

Figure 5: XRD spectra of mill scale. Source: Durowaye et al. [37].

4. Effect of steel mill scale on the properties of concrete

4.1. Steel mill effect on fresh concrete properties

The use of steel mill scale as an aggregate or supplementary material in concrete can impact the fresh concrete properties in several ways, such as the setting times and workability.

4.1.1. Setting Time

The hydration process of concrete is influenced by the iron oxides in steel mill scale thereby affecting the setting time. Studies have shown that lower percentage replacement amounts impacted the settings times minimally, while higher dosages caused an extended setting period. Oyelade et al. [36] observed an increased initial and final setting times of cement paste containing pulverized steel mill scale (PSMS). At 5% replacement, an increase of 8.75 and 19.43% was observed in the initial and final setting times respectively, while at 40%, an increase of 49.3 and 65.87% initial and final setting times was observed thus confirming that PSMS is a setting time decelerator.

4.1.2. Workability

Concrete containing steel mill scale can experience reduced workability due to the high surface area which can increase the water demand. Ganeshprabhu et al. [18] observed that the slump cone and compaction factor test both showed a decrease in workability with increasing percentage of steel mill scale. A high percentage steel mill scale concrete may exhibit low workability hence may require workability enhancing admixtures after 60% replacement levels [31]. A study by Srikar & Rao [38] reported a shear slump for a steel mill scale at lower replacement percentages and true slump for a constant addition up to the total sand replacement. A decreased workability and a drop in the compaction factor values was recorded for a complete replacement of river sand (Fig. 6).

4.2. Steel mill effect on the properties of hardened concrete.

4.2.1. Density

The density of steel mill scale ranges typically between 4.5 g/cm^3 and 6 g/cm^3. Furlani & Maschio [29] reported a density of 5.65 g/cm^3, Alwaeli [4] reported a density of 4.72 g/cm^3. Singhal et al., [1] in his study reported a density of 5.6g/cm^3. Reports of studies carried out show that concrete containing steel mill scale attained higher densities when compared to samples having more sand content [29, 31, 1, 4]. The study by Srikar & Rao [38] observed that for each 20% increment of steel mill scale the density increased by

Table 1: Particle size distribution of sand and steel mill scale.

Sieve size (mm)	M-Sand (% passing) [31]	Steel Mill Scale (% passing)	Sand (% passing) [11]	Steel Mill Scale (% passing)	Steel Mill Scale (% passing) [30]
4.75	98.2	95.5	94	84.2	100
2.36	91.78	85.3	85	34.2	90.2
1.18	70.82	61.3	60.6	15.6	70.2
0.6	49.35	43.9	40	0.6	44.2
0.3	7.23	16.1	9.2	0	11.6
0.15	1.11	5.5	4	0	0.6
0.075	0.21	1.3	0	0	0
< 0.075	0.01	0	0	0	0

Table 2: Physical properties of Steel Mill Scale

Author	Color	Specific gravity	Water absorption (%)	Fineness modulus (%)
[31]	Bluish black	4.10	0.74	2.724
[34]	Bluish black	4.96	< 0.5	-
[33]	-	5.90	0.81	-
[30]	-	6.06	0.604	-
[11]	-	6.02	-	5.35
[35]	-	4.49	-	4.91
[15]	Blue-gray	2.03	0.75	-
[32]	-	4.58	-	2.51
[8]	-	6.20	-	5.85

Table 3: Chemical composition of steel mill scale in % weight.

Author	Fe O	Mn O	Al_2O_3	Si O_2	Ti O_2	Cu O	Ca O	Mg O	Na_2O	L O I
[9]	67.7	1.01	-	0.7	-	0.38	0.13	0.1	0.02	-
[32]	71.87	-	1.15	8.17	-	-	4.80	0.61	-	-
[18]	72.55	-	31.44	4.58	-	-	1.53	0.99	-	4.29
[7]	72.12	0.47	0.22	-	-	-	-			
[23]	72.12	0.47	0.22	0.55	-	-	0.62	-	-	-
[36]*	2.41	-	29.86	21.64	-	-	30.11	29.86	0.13	12.19
[14]	96.5	1.02	0.16	0.68	-	0.4	0.13	0.10	0.04	1.1
[35]	74.06	-	0.06	25.88	-	-	-	-	-	-
[6]	68.20	0.48	-	0.25	-	0.47	0.13			
[15]	93.61	1.53	0.099	1.87	0.014	-	0.11	0.28	0.013	-
[10]	72.13	0.37	-	0.14	-	-	0.42	-	-	-
[29]	96.31	1.55	0.15	-	0.47	-	-	-	-	-
[37]	68.809	0.024	-	0.011	-	-	0.220	0.016	-	0.001

*Pulverized Steel Mill Scale

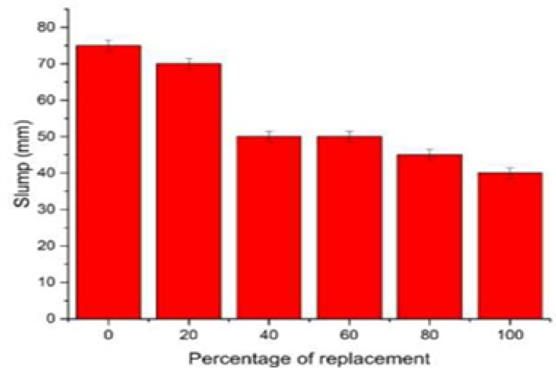

Figure 6: Slump of steel mill scale concrete. Source: Srikar & Rao [38].

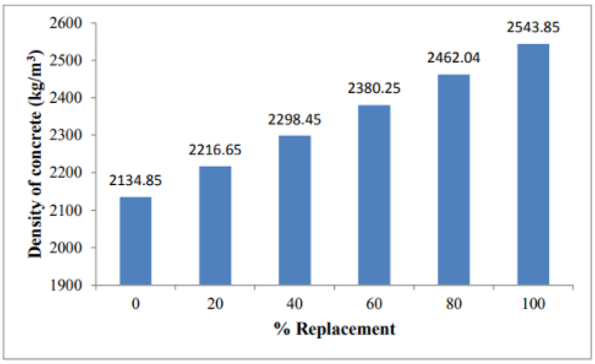

Figure 7: Density of steel mill scale concrete. Source: Srikar & Rao [38].

around 4%, 8%, 12%, 15%, and 19% respectively (Fig. 7). Alwaeli [4] observed an increase in concrete density of 30.56%, while Singhal et al. [1] observed a 38.56% increase in density at full sand replacement above the control. Hence, steel mill scale can be used for making high-density concrete that has various applications like pavement concrete, gravity dam and so [33].

4.2.2. Mechanical properties

The incorporation of steel mill scale in concrete has shown to potentially increase the mechanical strength of concrete [39].

Mahendran [35] explored the feasibility of partially replacing cement and fine aggregate with Fly Ash and Steel Mill Scale respectively in concrete at various proportions using an increment of 5%, from 20% to 30% with a water cement ratio of 0.45 and a grade 30 concrete. It was observed that with fly ash and steel mill scale replacement of 25% each, the obtained concrete was more than the concrete design strength. The study recommended the production of sustainable concrete using 25% replacement of cement and fine sand with fly ash and steel mill respectively.

Akhinesh et al. [11] in a study observed a strength increase for the sand replacement by the mill scale proportion from 5% to 15% and then a decreasing trend. The maximum compressive strength of was obtained by using 15% of mill scale. However, 5% and 15% mill scale replacement was recommended for practical purposes.

Singhal et al., [1] studied the compressive and split strength of grade 35 concrete that was prepared using a water cement of 0.4 with varying mill scale content of fine aggregate from 0% to 80%. The study concluded that the optimal steel mill scale replacement was at 40%. Also that more water was required to maintain the workability for concrete containing steel mill scale.

Alwaeli [4] observed that concrete containing steel chips outperformed conventional concrete in terms of compressive strength, while concrete having more than 25% aggregate replacement showed a decline in strength.

Furlani & Maschio [29] concluded from the study that there was no significant decrease in mechanical strength as a result of the steel mill scale additions. However, the significant decrease in compression strength observed in materials containing the highest amount of steel mill scale was due to their residual porosity, more than as an effect of the SMS addition.

Rameswaram et al. [33] in a study reported the compressive strength of the M20 grade concrete increased 1.5 times the controlled specimen and peaked at an optimal replacement of sand at 25% of steel mill scale.

Murthy [16] carried out a study to ascertain the suitability of mill scale as fine aggregates in concrete. His study reported that steel mill scale is an inert material and can be used as a filler material. Also, steel mill scale exhibits no lime reactivity and hence can be used for aggregate replacements and not as a binder in concrete. Results suggested a possible aggregate replacement of up to 40%.

Srikar and Rao [38] observed a corresponding increase in compressive strength of 10.5%, 16.3% and 32.3% respectively for every 20% of sand replaced with steel mill scale, in a replacement range of 20 to 100%. However no noticeable increase in strength was observed for 80% and 100% replacement.

Khan et al., [32] reported in a study a 1.24 and 1.74 times higher concrete compressive strength and flexural strengths than the control sample after 7 and 28 days for a replacement of 20% of fine aggregates with steel mill scale respectively. The research recommended 20% as the optimal steel mill scale sand replacement in concrete and its utilization as a suitable material for heavyweight concrete members and radiation shield structures.

According to Tiwari [34] the maximum compressive strength of concrete occurs when sand is replaced with 40% steel mill scale, and the strength can increase up to 60%. He concluded that the replacement of sand with mill scale is feasible up to 80% replacement.

Parvathikumar et al. [31] **i**nvestigated the influence steel mill scale on fresh and hardened concrete paving blocks properties. M-sand was replaced at intervals of 20% from 0% to 100% using a constant w/c ratio of 0.5 and a target strength of 30N/mm^2. A 60% replacement was recommended as this replacement level exhibited the highest compressive and split strength.

A study by Thoriya et al. [3] reported that owing to the iron availability in SMS, both compressive and tensile strength results were desirable up to 15% replacement and that based on the all results, 15% replacement gives an encouraging result.

Although steel mill scale has optimal replacement levels, reports have shown that steel mill scale concrete exhibited higher strength than control specimen at 100% sand replacement [31], [38].

For Ilutiu – Varvara et al. [40] both the compressive and flexural strengths of concrete having aggregates replaced with steel mill scale fell short of the standard sample. An increase in steel mill scale further decreased the mechanical properties of the concrete produced when compared to the standard specimen.

The utilization of steel mill scale as cement replacement in concrete has also been reported. Chousidis et al., [39] in an experimental study of cement mortars and reinforced concrete using mill scale as cement replacement in proportions of 5% and 10% by weight of cement, reported an improved compressive strength of the concrete.

Oyelade et al. [36] studied the effect of pulverized steel mill scale (PSMS) on the compressive strength of concrete and the effect of an elevated temperature on the concrete produced. A compressive strength reduction at 5% PSMS replacement was observed. However at 10% replacement, steel mill scale replaced concrete exhibited strength which was 4.5% greater than the control sample. The study concluded that the optimal cement replacement using pul-

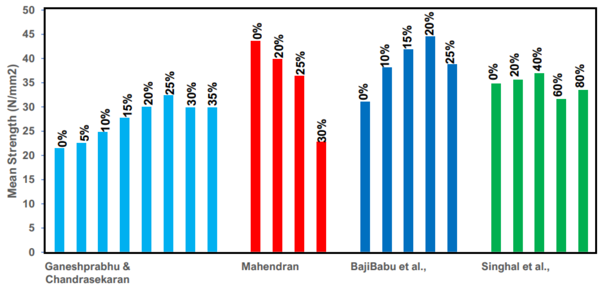

Figure 8: Compressive strength results by previous researchers [1, 8, 30, 35].

verized steel mill scale is 10% and at this replacement, and that at a temperature below 500°C, concrete strength was not adversely affected. Fig. 8 shows some of the optimal steel mill scale values as obtained by previous researchers. Table 4 presents some mechanical properties of concrete containing steel mill scale.

4.3. Durability

Concrete structures are expected to perform admirably mechanically throughout the long term. The measure of it's robustness and durability depends on the ability to resist loads, bear it's weight and withstand any form of deterioration mechanically, chemically or physically for as long as it is intended to serve it's purpose [38].

4.3.1. Water absorption

Water absorption is a crucial factor that directly impacts the concrete's performance in terms of durability, strength, and resistance to environmental factors. Several studies have shown that concrete containing steel mill scale exhibits lower water absorption compared to concrete with natural aggregates.

Parvathikumar et al. [31] observed a high water absorption level in concrete incorporating 0% steel mill scale as compared to sand replaced specimens with the relatively lowest absorption levels at 60% replacement levels. This phenomenon is also reported by several other researchers [15, 29, 34]. Table 2 presents some of these values.

4.3.2. Corrosion Resistance

The presence of iron oxides in mill scale can contribute to the overall resistance against corrosion by enhancing the passive layer on steel reinforcement. This is mostly attainable at optimal replacement levels where the concrete matrix is densified. Concrete with moderate amounts of mill scale have been reported to exhibit corrosion resistance comparable to concrete made with conventional aggregates, nonetheless, with adequate curing and compaction. Akhinesh et al. [11] in their study concluded that mill scale concrete can be used to protect constructed pavements from corrosion. Steel mill scale influences the corrosion resistance of steel rebars in concrete [39, 44]. A study by Doi et al. [45] revealed a reduction in the corrosion resistance of steel rebars with the inclusion of steel mill scale in concrete mortars.

4.3.3. Chloride Penetration

Concrete resistance against the ingress of aggressive ions is one of the major factors from the viewpoint of concrete durability [46]. Mill scale can reduce the permeability of concrete, thereby limiting chloride ion penetration and enhancing durability. The effect is most pronounced at optimal replacement levels where the concrete matrix is densified without compromising workability

Chousidis et al. [39] studied the effect of steel mill scale on chloride penetration resistance. Reports from the study indicate an increased resistance of reinforced cementitious composites to chloride penetration.

4.3.4. Sulphate Resistance

Sulphate attack is a form of deterioration capable of causing cracking and structural damage in concrete. It is a significant concern in environments with high sulphate concentrations, such as coastal areas or regions with sulphate-rich soils and groundwater. A study by Khan et al. [32] indicates that the use of steel mill scale in concrete increases its sulphate resistance.

4.3.5. Thermal conductivity

Steel mill scale has a higher thermal conductivity than aggregates, hence incorporating steel mill scale in concrete can increase it's thermal conductivity [47]. Thermal conductivity, (although not a core durability property) affects temperature gradients, moisture movements, and fire resistance. High thermal conductivity infers significant temperature gradients that over time can cause thermal stresses leading to cracking and deterioration. However, low thermal conductivity materials, by means of a slow heat transfer helps to maintain the structural integrity of concrete exposed to fire. An improvement in thermal conductivity of concrete can be achieved at 10% by weight of steel mill scale addition [29].

4.4. Microstructural properties

Owing to the high-temperature oxidation process of steel, steel mill scale has a rough and angular surface texture. Scanning Electron Microscopy (SEM) conducted by previous researchers clearly showed steel mill scales are irregular in shape with an uneven form and a harsh surface roughness [18, 38]. Also, at 60% steel mill scale replacements, better microstructural outcomes were achieved as the concrete was densely packed with averagely small pore sizes and as such performed better in tests [18, 31]. This is attributed to it's amorphous nature as opposed to the crystalline nature of river sand [38].

4.5. Road construction material applications of the steel mill scale

Steel mill scale has emerged as a potential solution in the improvement of soil properties for road construction. Significant results have been reported by adding steel mill scale dust to expansive soils [48]. These results further show that the standard compaction test and CBR values of soils treated steel mill scale exhibited a remarkable improvement. Satyanarayana et al. [49] observed that addition of mill scale dust increased the soaked CBR of the tropical black cotton soil and MDD optimally at 15 % mill scale dust content. Incorporating steel mill scale in soils has also been reported to significantly reduce it's plasticity index. Murthy [15] reported a three times increase in the CBR and manifold increase in permeability of black cotton soil mixed with 15% mill scale, also a remarkable decrease in plasticity at a 12% steel mill scale replacement was observed.

4.6. Electromagnetic applications of the steel mill scale

Steel mill scale composed of iron oxides is potentially an electromagnetic shielding material owing to its conductive abilities. Hence, it's incorporation in concrete can enhance the electromagnetic shielding properties of concrete. Ozturk et al., [42] in a study compared the mechanical and EM shielding properties of mortars with the control. The results indicated that mill scale replaced mortars had almost the same mechanical and better EM shielding properties compared to the control mortar. Hence, such concrete can be employed for construction where radiation is used [5], [32], [50].

Table 4: Summary of the mechanical performance of concrete. Modified after Ahmad et al. [43].

Ref	Range (%)	Concrete type	Substitution	W/C	Slump range	Optimal (%)	Age (Days)	% increase or decrease of strength	Remarks
[30]	0-35	Grade 20	Sand	0.46	-	25	28	50.7%	Improved strength
[35]	20-30	Grade 30	Sand	0.45	-	-	28	-	Strength Decline
[38]	20-100	-	Sand	-	40-75	60	28	32.3%	Improved Strength
[16]	0-60	M20/25	Sand	-	22-85	40	28	-	-
[36]	0-40	-	Cement	-	15.8-73.5	10	28	-	-
[34]	0-80	Grade 30	Sand	-	52-74	40	28	10.7%	Improved strength
[11]	0-50	1:1.5:3	Sand	0.45	-	15	7	37.25%	Improved strength
[32]	0-40	1:2.42:3.30	Sand	0.57	-	20	7	24.7%	Improved strength
[29]	0-40	1:3	Sand	0.32		10	28	-	Decreased strength
[4]	25-100	-	Sand	-	-	25	28	13.8%	Increased strength
[41]	0-100	Grade 30	Sand	-	-	30	28	-	-
[42]	0-30	1:2.75	Sand	0.485	-	15	28	23.12	Increased strength
[8]	0-25	M25	Sand	0.45	-	20	28	30	Increased strength
[1]	0-80	M35	Sand	0.40	-	40	28	6.32	Increased strength

It has been observed to counter X-ray radiation and can therefore be used as an alternative to conventional concrete in radiation attenuation activities [4].

5. Conclusion

Steel mill scale contributes to sustainable construction practices by reducing waste, conserving resources, and promoting energy efficiency, making it a valuable component of modern, eco-friendly construction. This article provides an overview through an analysis of recent studies and practical applications, the current state of research on SMS by examining the strength, workability, durability characteristics, environmental benefits and the challenges of concrete modified using steel mill scale.

The following are the conclusions that have been made.

- Steel mill scale is a bluish black coloured, flaky or scale-like by product of the steel making process. It consists majorly varying proportions of iron oxides such as Wustite (Fe O), Magnetite (Fe_3O_4), Hematite (Fe_2O_3).
- The density and surface texture of steel mill scale is comparatively higher and rougher than natural aggregates used in concrete.
- Steel mill scale can be utilized for several purposes such as in the steel industry, waste water and soil treatments, road construction, aggregates in concrete, EM radiation shielding etc.
- The incorporation of steel mill scale in concrete offers several benefits such as higher density, improved mechanical strength, and enhanced durability.
- At moderate amounts of mill scale, a carefully controlled mix design can improve resistance to chloride ions penetration, sulphate attacks and corrosion.
- Steel mill scale impacts concrete's workability thereby requiring mix design alterations such as adjustment in the water-cement ratio or the use of superplasticizers. The effect on concrete's setting time is generally minimal at low replacement levels but can lead to slight delays at higher dosages.
- The optimal replacement ratio of natural aggregate with steel mill scale in concrete varies depending on specific requirements and desired properties of the concrete. Practical considerations shows that the optimal replacement levels for improved mechanical properties ranges between 10-30%. However, for a carefully designed and well compacted mix, total sand replacement with steel mill scale can also produce concrete that outperforms the control specimen.
- Pulverized steel mill scale has the potential to replace cement in concrete production.

5.1. Further research

From the review, it is clear that the potential of steel mill scale as a concrete producing material has not been extensively tested. Areas of further research includes studying the long-term performance of concrete with mill scale is essential to fully understand its behaviour under various environmental conditions and loadings. Furthermore, almost all research carried out on the steel mill scale replacement in concrete has been on the replacement of aggregates and very little on the potentials of incorporating steel mill scale as cement replacement. This can be attributed to the fact that the chemical composition of the steel mill scale does not suggest that it possess any pozolonic properties. However, research has shown that it's pulverization can lead to an alteration in the chemical properties thereby acquiring some pozzolanic properties that makes it fit to have some binding abilities. Based on the foregoing, this literature review suggests a wider research on steel mill scale's cement replacement potentials.

References

[1] Singhal A, Bhunia D & Pandel B, Effect of sand replacement by mill scale on the properties of concrete, *Int. J. Eng. Technol. Sci. Res.*, 2 (2015) 60–67.

[2] Liman A Z, Adagba T & Umar H A, Effect of crushed doum palm shell as partial replacement of coarse aggregate in concrete, 4(4) (2021) 1–9. ISSN 2645-2944. https://doi.org/10.33003/fjs-2020-0404-456.

[3] Rasikbhai Thoriya K, Singh A, Agrawal V & Chandra Gupta R, Preliminary study on utilization of steel mill scale in concrete. ISSN 2214-7853. https://doi.org/10.1016/j.matpr.2023.04.062.

[4] Alwaeli M, The implementation of scale and steel chips waste as a replacement for raw sand in concrete manufacturing, *J. Clean. Prod.*, 137 (2016) 1038–1044. ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2016.07.211.

[5] Alwaeli M & Nadziakiewicz J, Recycling of scale and steel chips waste as a partial replacement of sand in concrete, *Constr. Build. Mater.*, 28(1) (2012) 157–163. ISSN 0950-0618. https://doi.org/10.1016/j.conbuildmat.2011.08.047.

[6] Martín M I, López F A & Torralba J M, Production of sponge iron powder by reduction of rolling mill scale, 39(3) (2012) 155–162. ISSN 1743-2812. https://doi.org/10.1179/1743281211y.0000000078.

[7] Sista K S, Dwarapudi S, Kumar D & Sinha G R, Physicochemical properties of mill scale iron powders, 60(8) (2020) 1669–1674. ISSN 1347-5460. https://doi.org/10.2355/isijinternational.isijint-2019-737.

[8] BajiBabu E, Babu Y S & Gajalakshmi G, Comparative study on compressive strength of concrete by partial replacement of fine aggregate with mill scale and combination of mill scale with rice husk ash, *International Journal of Creative Research Thoughts (IJCRT)*, 6(2) (2018) 309–312.

[9] El-Shiekh H, El-Fawakhry M K, Mitwally M E & Shash A Y, Production of reduced iron from mill scale waste using tilting rotary furnace, 19 (2023) 100429. ISSN 2590-048X. https://doi.org/10.1016/j.rinma.2023.100429.

[10] Benchiheub O, Mechachti S, Serrai S & Khalifa M G, Elaboration of iron powder from mill scale, *J Mater Env. Sci.*, 1(4) (2010) 267–276.

[11] Akhinesh K, Jithu G F, Junaid K T, Jishnulal K, Jeril N J & Remya N, Study of the compressive strength of concrete with various proportions of steel mill scale as fine aggregate, *IOSR J. Mech. Civ. Eng. IOSR-JMCE* (2015) 104–109.

[12] Predescu A M, Matei E, Berbecaru A C, Râpă M, Sohaciu M G, Predescu C & Vidu R, An innovative method of converting ferrous mill scale wastes into superparamagnetic nanoadsorbents for water decontamination, 14(10) (2021) 2539. ISSN 1996-1944. https://doi.org/10.3390/ma14102539.

[13] Cho S, Metal recovery from stainless steel mill scale by microwave heating, 14(2) (2008) 193–196. ISSN 1598-9623. https://doi.org/10.3365/met.mat.2008.04.193.

[14] Eissa M, Ahmed A & El-Fawkhry M, Conversion of mill scale waste into valuable products via carbothermic reduction, 2015 (2015) 1–9. ISSN 1687-9473. https://doi.org/10.1155/2015/926028.

[15] Murthy Y I, Stabilization of expansive soil using mill scale, *Int. J. Eng. Sci. Technol.*, 4(2) (2012) 629–632.

[16] Murthy Y I, On the mechanical aspects concrete containing mill scale, 8(8) (2021) 23–34. ISSN 2348-8352. https://doi.org/10.14445/23488352/ijce-v8i8p103.

[17] Alghtani A H, Alsharef M & El-Aziz K A, Characterization of iron powder produced by reduction of hot-rolled mill scale in hydrogen gas, *Mater. Res.*, 25 (2022) e20210575. ISSN 1516-1439. https://doi.org/10.1590/1980-5373-mr-2021-0575.

[18] Ganeshprabhu P, Chandrasekaran P & Farzana A S, Engineering behaviour of sustainable concretewith steel mill scale, 30(2) (2021) 1129–1137. ISSN 2083-5906. https://doi.org/10.15244/pjoes/124895.

[19] Murthy Y I, Agarwal A & Pandey A, Characterization of mill scale for potential application in construction industry, *Indian J. Eng.*, 14(35) (2017) 71–76.

[20] El-Hussiny N A, Abdul-Wahab H H, Ali M M, Omar A L A M, Shalabi M E M H & Moharm M R, Effect of grinding time of mill scale on the physicochemical properties of produced briquettes and its reduction via hydrogen, 01(07) (2014) 1–10. ISSN 2333-9721. https://doi.org/10.4236/oalib.1101016.

[21] Gaballah N M, Zikry A F, Khalifa M G, Farag A B, El-Hussiny N A & Shalabi M E H, Production of iron from mill scale industrial waste via hydrogen, 03(03) (2013) 23–28. ISSN 2164-6805. https://doi.org/10.4236/ojinm.2013.33005.

[22] Nowacki K, Maciąg T & Lis T, Recovery of iron from mill scale by reduction with carbon monoxide, 11(5) (2021) 529. ISSN 2075-163X. https://doi.org/10.3390/min11050529.

[23] Sista K S, Dwarapudi S & Nerune V P, Direct reduction recycling of mill scale through iron powder synthesis, 59(5) (2019) 787–794. ISSN 1347-5460. https://doi.org/10.2355/isijinternational.isijint-2018-628.

[24] Afshar M, Karimi G & Mozaffari E, Introducing a recycling method for iron oxide nanoadsorbent from mine waste and its application in wastewater treatment, 17.

[25] Matei E, Predescu A, Vasile E & Predescu A, Properties of magnetic iron oxides used as materials for wastewater treatment, 304 (2011) 012022. ISSN 1742-6596. https://doi.org/10.1088/1742-6596/304/1/012022.

[26] Sulaiman S, Azis R S, Ismail I, Man H C & Rosdi N, Rapid adsorption of magnetite nanoparticles from recycled mill scale waste as potential adsorbent for removal of cu(ii) ions, 317 (2021) 270–275. ISSN 1662-9779. https://doi.org/10.4028/www.scientific.net/ssp.317.270.

[27] Ma N, Houser J B & Wood L A, Production of cleaner mill scale by dynamic separation of the mill scale from the fast-moving flume water at a hot rolling mill, 176 (2018) 889–894. ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2017.12.039.

[28] Bhunia D & Singhal A. Effect of sand replacement by mill scale on the properties of concrete (2015). URL http://dspace.bits-pilani.ac.in:8080/jspui/xmlui/handle/123456789/7878, int. J. Eng. Technol. Sci. Res.

[29] Furlani E & Maschio S, Steel scale waste as component in mortars production: An experimental study, 4 (2016) 93–101. ISSN 2214-5095. https://doi.org/10.1016/j.cscm.2016.02.001.

[30] Ganeshprabhu P & Chandrasekaran P, Zero waste management and green steel by replacement of steel mill scale in eco friendly construction, *Eco Env Cons*, 24(4) (2018) 1690–1695.

[31] Parvathikumar G, Balachandran G B & Sahadevan B, Performance of green concrete paving block imbibed with industrial scrap steel mill scale for sustainable construction, 10(3) (2023) 035505. ISSN 2053-1591. https://doi.org/10.1088/2053-1591/acc56b.

[32] Khan M A, A study of concrete incorporating steel mill scale waste, 17(6). ISSN 2454-7190. https://doi.org/10.26782/jmcms.2022.06.00001.

[33] Rameswaram P M, Jothilingam M & MohanaRam M, Potentiality of steel mill scale as raw material for concrete as fine aggregate, 05(05) (2018) 3907–3909.

[34] Tiwari S, Effect on mechanical properties of concrete using mill scale as a partial replacement of fine aggregate, *Eng. Technol. J. Res. Innov. ETJRI* (2022) 6–8. Vol. IV, no. II.

[35] Mahendran K, Use of fly ash and steel mill scale in cement concrete as alternate building materials, *Int. J. Earth Sci. Eng.*, 06(02) (2013) 109–111.

[36] Oyelade A, Odegbaro D & Fapohunda C, Effect of elevated temperature on the compressive strength of concrete produced with pulverized steel mill scale, 36(4) (2018) 1030. ISSN 0331-8443. https://doi.org/10.4314/njt.v36i4.6.

[37] Durowaye S I, Sekunowo O I, Lawal A I & Ojo O E, Development and characterisation of iron millscale particle reinforced ceramic matrix composite, 11(4) (2017) 634–644. ISSN 1658-3655. https://doi.org/10.1016/j.jtusci.2016.08.005.

[38] Srikar K & Rao M K, The benefits of using refurbished steel mill scale for fine aggregate on concrete performance, *Webology*, 18(1) (2021) 1981–1989.

[39] Chousidis N, Rakanta E, Ioannou I & Batis G, Influence of iron mill scale additive on the physico-mechanical properties and chloride penetration resistance of concrete, 28(6) (2016) 389–402. ISSN 1751-7605. https://doi.org/10.1680/jadcr.15.00129.

[40] Ilutiu Varvara D A, Aciu C, Tintelecan M & Sas Boca I M, Assessment of recycling potential of the steel mill scale in the composition of mortars for sustainable manufacturing, 46 (2020) 131–135. ISSN 2351-9789. https://doi.org/10.1016/j.promfg.2020.03.020.

[41] Sree Lakshmi Devi G & Venkata Siva Rama Prasad C, Influence of stress-strain behaviour of quaternary blended self compacting concrete for sustainable construction, 1086(1) (2022) 012007. ISSN 1755-1315. https://doi.org/10.1088/1755-1315/1086/1/012007.

[42] Ozturk M, Depci T, Bahceci E, Karaaslan M, Akgol O & Sevim U K, Production of new electromagnetic wave shielder mortar using waste mill scales, 242 (2020) 118028. ISSN 0950-0618. https://doi.org/10.1016/j.conbuildmat.2020.118028.

[43] Ahmad J, Arbili M M, Alabduljabbar H & Deifalla A F, Concrete made with partially substitution corn cob ash: A review, *Case Stud. Constr. Mater.*, 18 (2023) e02100. ISSN 2214-5095. https://doi.org/10.1016/j.cscm.2023.e02100.

[44] Ming J, Shi J & Sun W, Effect of mill scale on the long-term corrosion resistance of a low-alloy reinforcing steel in concrete subjected to chloride solution, 163 (2018) 508–517. ISSN 0950-0618. https://doi.org/10.1016/j.conbuildmat.2017.12.125.

[45] Doi K, Hiromoto S, Shinohara T, Tsuchiya K, Katayama H & Akiyama E, Role of mill scale on corrosion behavior of steel rebars in mortar, 177 (2020) 108995. ISSN 0010-938X. https://doi.org/10.1016/j.corsci.2020.108995.

[46] Ramalingam V, Shainsha J, Harshitha M & Ramadoss O, Study on the mechanical property, water absorption, and acid resisitance of steel and polypropylene hybrid fiber reinforced recycled aggregate concrete, 67(2) (2024) 69–81. ISSN 2217-8139. https://doi.org/10.5937/GRMK2400004R.

[47] Baghel R, Pandel U & Vashistha A, Manufacturing of sustainable bricks: Utilization of mill scale and marble slurry, *Mater. Today Proc.*, 26 (2020) 2136–2139. ISSN 2214-7853. https://doi.org/10.1016/j.matpr.2020.02.460.

[48] Mohan A & Priyanka L, An experimental study on strength characteristics of expansive soil treated with mill scale, *Int. J. Innov. Res. Sci. Eng. Technol.*, 6(1) (2017) 837–844.

[49] Satyanarayana G N, Prasad S D & Raju P, Effect of steel mill scale dust and bamboo fibres on the strength characteristics of expansive soil, *Int. J. Eng. Sci. IJES*, 7(8) (2018) 33–38.

[50] Alwaeli M, Investigation of gamma radiation shielding and compressive strength properties of concrete containing scale and granulated lead-zinc slag wastes, *J. Clean. Prod.*, 166 (2017) 157–162. ISSN 0959-6526. https://doi.org/10.1016/j.jclepro.2017.07.203.