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Steel Mill Scale As A Sustainable Material In Concrete: Impact On Mechanical And Durability Characteristics

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Concrete is a predominant construction material known for its strength, durability, and versatility. In recent years,the rapid growth in various sectors including population increase have led to an escalating demand for construction materials and the consumption of natural raw materials.The integration of supplementary cementatious materials (SCMs) has gained traction to improve concrete's properties, with steel mill scale (SMS) emerging as a significant option. SMS, a byproduct of stainless steel manufacturing units, is often viewed as hazardous waste, but its incorporation into concrete can promote sustainable construction practices. By utilizing SMS, the environmental impact of steel production can be mitigated, reducing waste and leveraging a material that would otherwise be discarded.

In this paper, SMS is employed as a partial replacement for river sand in M30 concrete at varying rates of 5%, 10%, 15%, 20%, and 25%. The hardened properties of the concrete were assessed through tests for compressive strength, density, water absorption, flexural strength, and split tensile strength. To understand the impact of this alternative material on the durability of concrete, various durability tests were conducted, including assessments of strength variation under acid attack, weight variation due to acid exposure and chloride-ion penetration tests. The findings revealed that a replacement rate of up to 15% SMS yielded optimal results, enhancing the mechanical properties and durability of the concrete while contributing to sustainability. This research underscores the potential of SMS as an effective SCM, promoting both performance and environmental benefits in concrete applications.

Keywords: Conventional concrete, Durability, Mechanical Strength, Steel Mill Scale (SMS), Sustainability, Waste utilization.

1. Introduction

Concrete is a fundamental material in civil engineering, extensively utilized for its versatility and strength. Traditionally, natural river sand has served as the predominant fine aggregate in concrete. However, the growing global shortage of natural aggregates, coupled with increasing environmental concerns, has prompted the construction industry to seek alternative materials. These alternatives often include industrial byproducts or recycled materials, which not only reduce reliance on natural resources but also address the critical issue of waste disposal. One such industrial byproduct is Steel Mill Scale (SMS), generated during the stainless steelmaking process.Steel Mill Scale (SMS)is mostly non-toxic, trace metals like chromium, nickel, copper, etc. may be present and that pose environmental risk if improperly managed. It is hazardous to human health and is frequently dumped in secured landfills.

This study provides an opportunity to replace conventional aggregates by SMS in concrete, contributes to the sustainable management of industrial waste, transforming what would otherwise be a pollutant into a valuable construction material.The importance of utilizing waste materials in sustainable construction cannot be overstated. The construction industry is one of the major consumers of natural resources, and the depletion of these resources poses significant challenges for future development. By integrating waste materials like SMS into concrete production, we can significantly reduce the environmental footprint of construction activities.This approach equates with several Sustainable Development Goals (SDGs), particularly:SDG 9 (Industry, Innovation, and Infrastructure): Emphasizing the need for sustainable industrialization and resilient infrastructure, SDG 11 (Sustainable Cities and Communities): Advocating for sustainable urban development and SDG 12 (Responsible Consumption and Production): Focusing on reducing waste generation and promoting the reuse and recycling of materials. Hence, the incorporation of Steel Mill Scale in concrete production not only addresses the challenges of resource depletion but also fosters a more sustainable and responsible construction industry.

This study not only addresses the environmental impact of steel production by reducing waste but also supports the global shift toward more sustainable construction practices. By exploring the potential of Steel Mill Scale (SMS) in concrete, it contributes to the broader goal of creating more resilient and eco-friendly infrastructure, ultimately aiding in the achievement of these critical Sustainable Development Goals (SDGs).

Numerous studies have investigated the partial replacement of fine aggregates with steel mill scale (SMS) and steel scrap in concrete. For instance, RasikbhaiThoriya et al. (2023)[1] replaced fine aggregates with varying proportions of SMS. Other researchers, such as Venkatesan et al. (2021)[2], Velumani and Manikandan (2020)[3], Rameswaram et al. (2018)[4], Qasrawi (2018)[5], Singh and Siddique (2016)[6], Tao et al. (2016)[7], Mahendran (2013)[8], Etc., have explored the use of steel scrap, which has a coarser particle size, in the manufacture of concrete by replacing fine aggregates up to 30%. Venkatesan et al. used a combination of walnut shells and steel scrap in concrete. Singh and Siddique conducted research on self-compacting concrete using steel scrap. Mahendran studied the effects of replacing fine aggregates with fly ash and steel scrap in concrete.

After reviewing other studies, it was observed that they used steel scrap to replace fine aggregates, which has a higher specific gravity and bulk density. In this work, the authors utilized steel mill scale (SMS) in a fine powder form, which has a specific gravity similar to fine aggregates, resulting in a proper specific gravity of concrete compared to other studies using steel scrap. The primary reason for the disparity in specific gravity and particle size are the material form.

2. Experimental Procedure

A. Raw Materials

In this experiment, Ordinary Portland Cement (Grade 43, JK SUPER CEMENT) was used in accordance with IS 269:2015[9]. The cement's physical properties were tested as per the relevant IS standards. Natural river sand, passing through a 4.75 mm sieve, was used as fine aggregate, with its zone determined via sieve analysis per IS 383:2016[10]. Crushed natural aggregates, comprising equal parts of 20 mm and 10 mm sizes, served as coarse aggregates, with specific gravity, sieve analysis, and water absorption measured separately according to IS 2386(Part 3):1963[11]. Steel Mill Scale (SMS), a byproduct of the stainless steel industry incorporated mainly of iron oxides, was crushed into powder and used to partially replace fine aggregates in concrete. Water used in the mix met the quality standards for potable water. The properties of cement, aggregates and SMS are presented in Table I.

B. Mix Design and Sample Preparation

In this study, Fine aggregate was substituted with industrial waste steel mill scale. It was observed that the water-absorbing capacity of replacement material was very high compared to Fine aggregate, so we need to adding super-plasticizer. Based on trials, it was decided to increase the percentage of super-plasticizer and parallel replacement material utilized in surface saturated dry conditions.It was observed that 37% of the water is required to achieve a surface dry-saturated condition of steel mill scale (SMS). It was determined to conduct the primary casting process in six distinct groups (0%, 5%, 10%, 15%, 20%, and 25% replacement).In this research work, mix design was conducted as per IS 10262:2019[12]. Total six mixes were prepared including control mix. Firstly, raw material mixed in dry condition and then added water. Super-plasticizer, MasterGlenium SKY 8777 was added as per requirement to adjust compaction factor nearby 0.9.All material quantity for prepare mix listed in Table II.

In this analysis, we prepared samples in various forms, including cubes measuring 100 mm x 100 mm x 100 mm and 150 mm x 150 mm x 150 mm, cylinders with a height of 300 mm and diameter of 150 mm, and beams sized 100 mm x 100 mm x 500 mm, following the testing specifications. After a 24-hour casting period, we carefully removed all specimens from their moulds and proceeded with curing.

Table I Properties of Materials

Parameters	Cement	Coarse Aggregates 20 mm	10mm	Fine Aggregates	Steel Mill Scale (SMS)
Specific Gravity	3.18	2.85	2.75	2.59	2.57
Fineness	3%	7.95	7.11	2.25	-
Initial Setting Time	96 min	-	-	-	-

Final Setting Time	190 min	-	-	-	-
Normal Consistency	31%	-	-	-	-
Compressive Strength (3 days)	36 MPa	-	-	-	-
Compressive Strength (7 days)	42 MPa	-	-	-	-
Compressive Strength (28 days)	56 MPa	-	-	-	-
Water Absorption	-	0.24%	0.28%	1.5%	25.6%
Plastic limit	-	-	-	-	33.34%
Shrinkage limit	-	-	-	-	52.42%
pH	-	-	-	-	6.79
Bulk density	-	-	-	-	800 kg/m^3
Particle size	-	-	-	-	< 90 microns

Table II Mix Proportions

Mix	CM	RM5	RM10	RM15	RM20	RM25
Cement (kg/m^3)	381	381	381	381	381	381
Water (kg/m^3)	168	168	168	168	168	168
C.A of 20 mm (kg/m^3)	342	342	342	342	342	342
C.A of 10 mm (kg/m^3)	800	800	800	800	800	800
F.A (kg/m^3)	743.3	706.14	668.97	631.81	594.64	557.48
S.M.S. (kg/m^3)	0	37.16	74.33	111.49	148.66	185.82
Admixture (%)	0.8	0.9	1.0	1.1	1.2	1.3

3. Results and Discussion

In this study different properties of concrete in the fresh and hardening stages are studied. Workability and density were found in the fresh stage andremaining properties were found in the concrete hardened stage.

- **Workability**

The workability of concrete was determined using the compaction factor test, which was preferred over the slump test for its greater precision. The compaction factor values for all mixes were found to range from 0.90 to 0.95. Additionally, an increase in the percentage of replacement materials led to a corresponding increase in the quantity of super-plasticizers used, to archive the workability in the range from 0.90 to 0.95, is shown in Fig. 2.

- **Density**

The fresh density of concrete mixtures was determined in accordance with IS 1199(Part3) : 2018[15] by calculating the weight-to-volume ratio of fully compacted concrete, cylinders measuring 150 mm x 300 mm. Hardened density was evaluated using 150 mm cubes after 28 days of curing. These cubes were then oven-dried at 60° ± 5°C for 3 days, and the hardened density was computed by dividing the oven-dried weight, at room temperature, by the cube's volume. It was noted that as the replacement content increased, the density decreased. This reduction in density is attributed to the slightly lower specific gravity of SMS compared to fine aggregate, as well as the finer particle size of the replacement material.

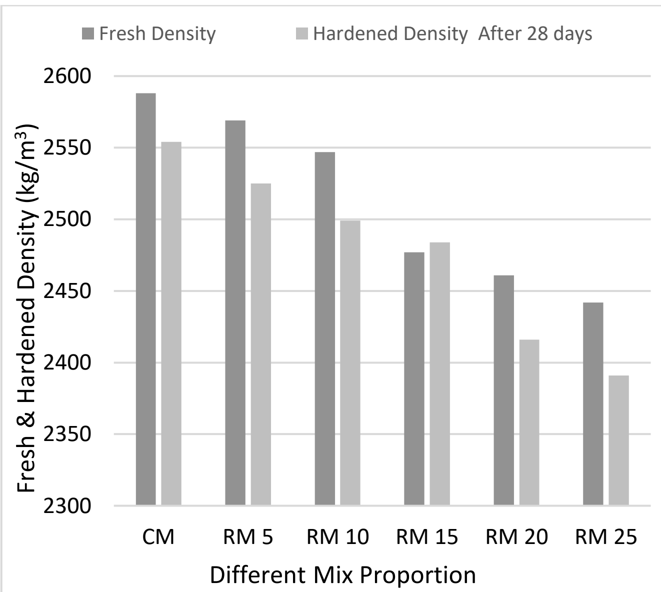

Fig. 1 Fresh and Hardened Density

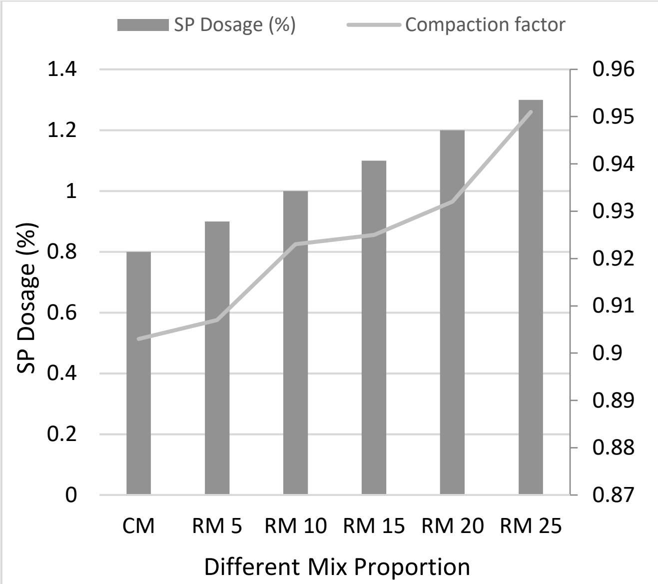

Fig. 2SP dosage and compaction factor at different mix

- **Compressive Strength**

The Compressive strength (IS 516: 1959)[13] was determined at various intervals of 7, 28, 56, 90, 180, and 365 days bytakenthree specifications of each and mean of that taken as final outcome. By the results we can conclude that 15% of replacementachieves the desired strength after 28 days. If the replacement percentage exceeds 15%, the desired strength cannot be attained. The study found that there was no statistically significant disparity in the compressive strength at both 7-day, 28-day and up to 365-days intervals when the replacement rate exceeded 15%. By considering only compressive strength, we can conclude from the Fig. 3 that the optimum replacement of SMS in concrete was 15%.

- **Flexural strength**

The flexural strength of concrete was assessed at various intervals, specifically at 28, 56, 90, 180, and 365 days after casting. For M30 grade concrete, the standard flexural strength is 3.83 MPa for 28 days as per IS 456 : 2000[16] but experimental results showed that control mix and 5% replacement of SMS achieved higher value than this standard value. At 10% replacement rate produced outcomes of flexural strength was slightly lower than the standard value, indicating that 10% is the optimal replacement level for achieving desired flexural strength. Additionally, after 90 days, the RM15 mix yielded results exceeding the standard value but following that, the percentage of replacement increased,the flexural strength decreased more rapidly.

- **Split Tensile Strength**

In this study, cylinder specimens with a height of 300 mm and diameter of 150 mmwere used to determine the split tensile strength of concrete as per IS 5816 : 1999[14]. The research findings indicate that the tensile strength of concrete initially increases up to a 10% replacement level, followed by a decline. Notably, the tensile strength of the concrete with steel mill scale (SMS) remained higher than that of the control mixture as long as the replacement level did not exceed 15%. The addition of steel mill scale contributed to an overall increase in tensile strength. After 56 days, the split tensile strength of the control mix (CM) was approximately 20% higher than that of the RM15 mix. Based on these results shown in Fig. 5, it can be concluded that the optimal use of SMS in concrete is at a 15% replacement level.

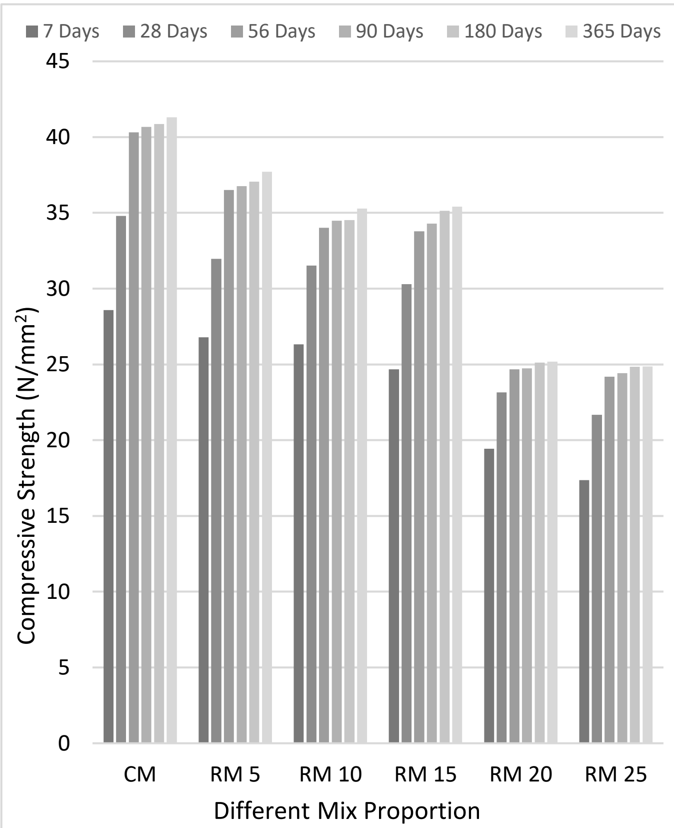

Fig.3 Compressive Strength of different ages

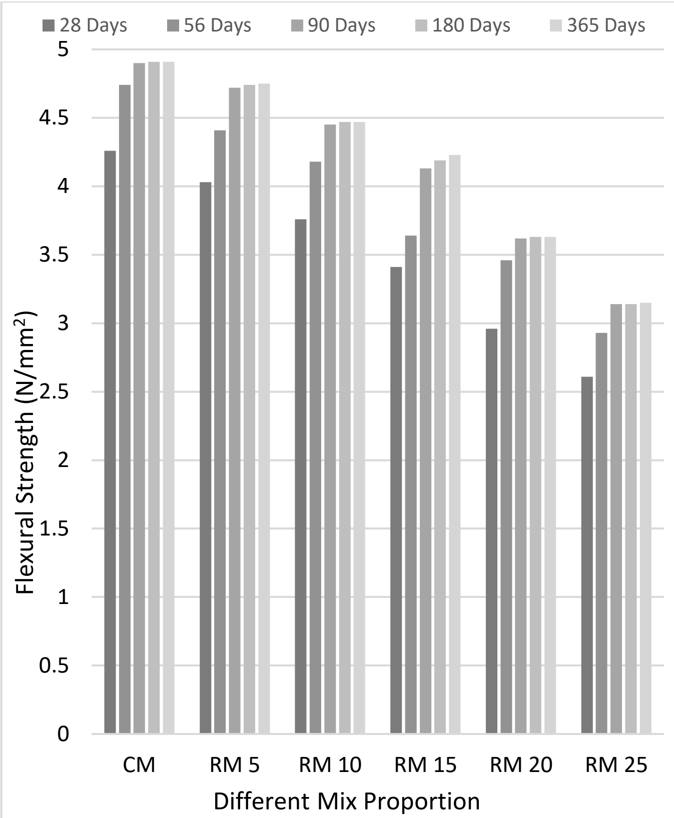

Fig.4 Flexural Strength of different ages

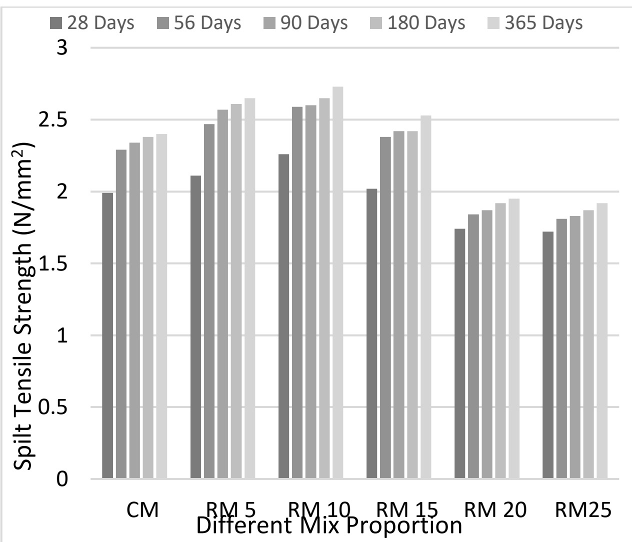

Fig.5 Split Tensile Strength of different ages

- **Weight Variation of Acid attack concrete**

In this test after 28 days water curing concrete specimen dipped in acid solution (3% H_2SO_4 by weight of water) as per ASTM C 267-97[17] and after removing the specimens from the acid solution, record the weight of the oven-dried sample and compare it to the non-acid attacked specimen's weight. As per graph, the weight of acid attack specimens decreases when compared to normal water curing specimens. In these results minimum weight loss occurred in RM20 mix proportion.

- **Strength Variation of Acid attack concrete**

For the strength test of acid-attack concrete, specimens were immersed in an acid solution prepared by adding 3% H_2SO_4 by weight of water. According to the results, the compressive strength of the acid-attacked specimens was lower than that of the normal specimens.

Following a 28-day immersion period, the compressive strength of the specimens subjected to acid attack was assessed and concluded increase in replacement percentage up to 20% strength loss deceased but after that again increased. Minimum value of strength loss in all design mixes was 13.33% for RM 20.

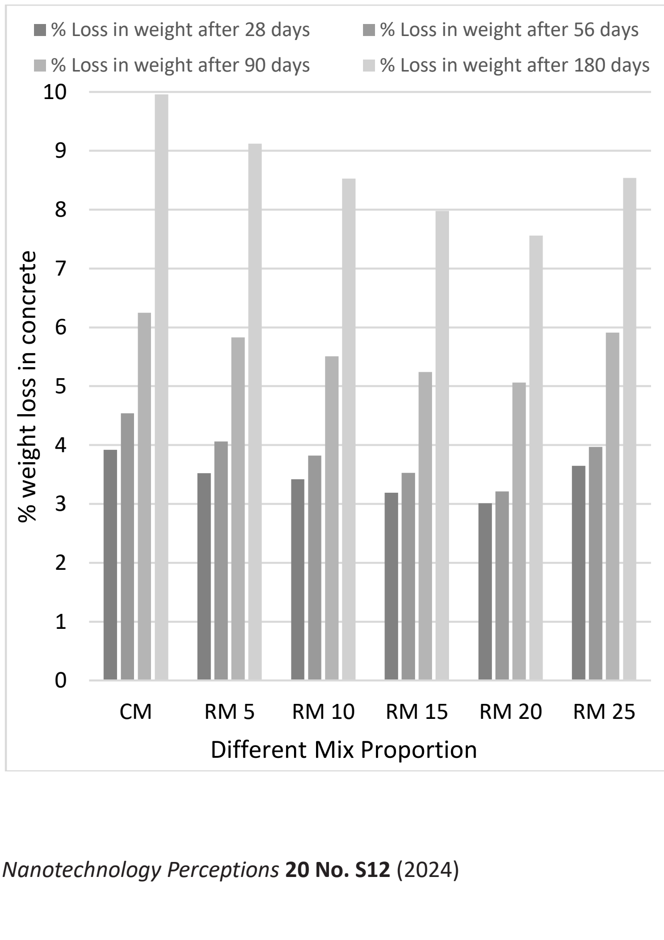

Fig.6Weight variation in acid attack concrete of different ages

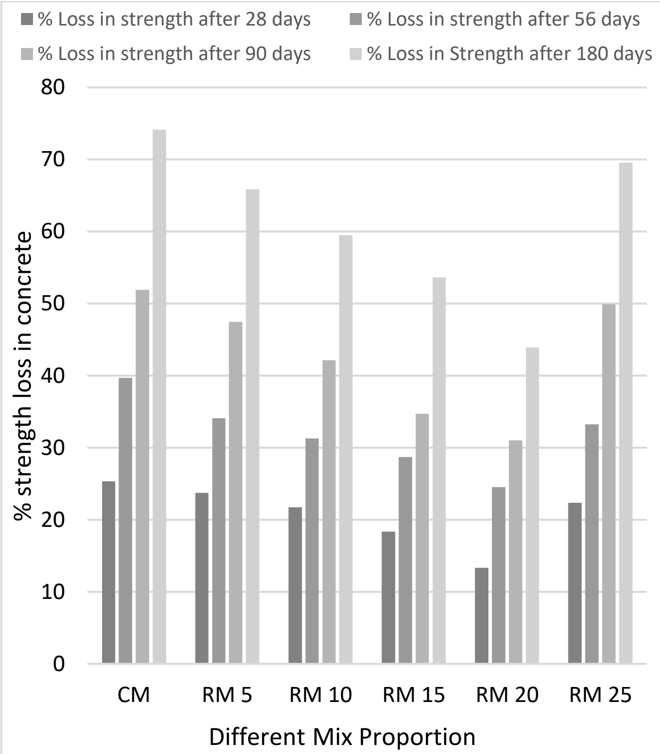

Fig.7 Strength variation in acid attack concrete of different ages

- **Chloride Penetration Test**

In this study, Concrete specimens dipped into the water in which 4%water weight NaCl added. It was observed that the depth of chloride penetration exhibited a progressive reduction with a maximum substitution of 15% using steel mill scale. When the SMS replacement percentage was increased upto 20% and 25%, the penetration depth also increased. The observed decrease in chloride penetration depth in concrete mixes containing S.M.S ranging from control mix to 15% can be attributed to the smaller size and impermeability of the steel mill particles, which effectively blocking the entry of chloride ions.

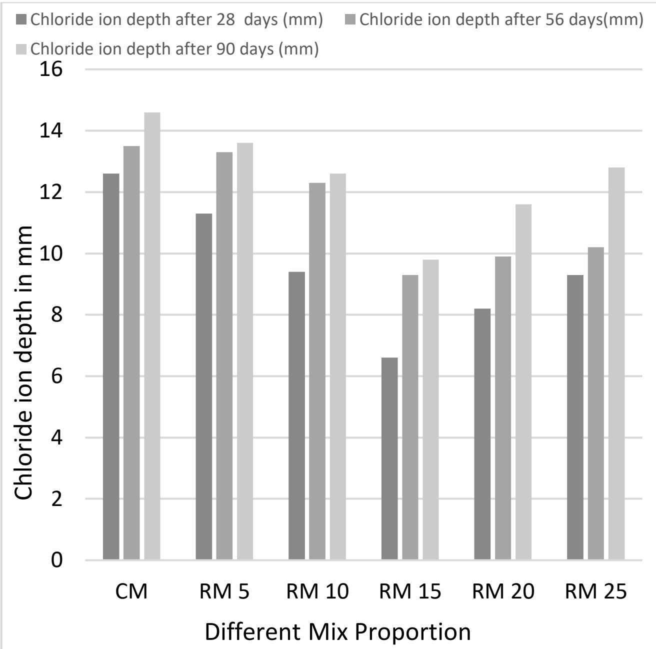

Fig.8 Chloride ion depth in concrete of different ages

4. Conclusions

This study concluded that increasing the replacement of steel mill scale (SMS) in concrete necessitates a higher dosage of water-reducing admixtures due to the material's finer particle size and greater water absorption. This adjustment achieves a compaction factor between 0.90 and 0.95. Fresh concrete exhibited a density that was 1% to 2% higher than that of hardened concrete, although both densities decreased as the replacement content increased. Compressive strength diminished with higher replacement levels; however, a minor reduction was observed with up to 15% replacement, while more significant reductions occurred beyond this threshold. Flexural strength also decreased with increased replacement, but up to 10% replacement remained within acceptable limits. Interestingly, tensile strength increased with up to 10% replacement and continued to be higher than that of the control mix at 15%, indicating that 15% replacement is optimal for both compressive and tensile strength.As the replacement ratio increases, the performance of the mix proportions improves, with RM 15 demonstrating the best durability by exhibiting the least chloride ion penetration and minimal strength loss and weight loss. In contrast, RM 20 and RM 25 performed poorly, showing higher values for chloride ion penetration.

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