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Research Article

Impact of manufactured sand grading method on durability of self-compacting concrete

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Abstract

This study examines the impact of different grading methods for manufactured sand (M-sand) on the mechanical and durability characteristics of self-compacting concrete (SCC). A detailed experimental program was designed to assess the mechanical and durability properties of SCC containing M-sand processed through two different grading techniques, air-graded M-sand (AGMS) and wet-graded M-sand (WGMS) in comparison with river sand (RS). AGMS & WGMS are used to replace RS in the proportion of 0%, 25%, 50%, 75% & 100%, and the mechanical and durability properties of the concrete have been evaluated. The findings reveal that the grading method has a notable influence on SCC performance. This study also examined the relationship between various durability properties like RCPT, water absorption and porosity using MATLAB. It was observed that AGMS and WGMS increased the compressive strength of M20 SCC by 29% and 14%, respectively. In M40 and M70 mixes, AGMS led to 14% and 13% increase, while WGMS resulted in 9% and 4%. Tensile strength improved by 26%, 25%, and 28% with AGMS, and 22%, 13%, and 26% with WGMS in M20, M40, and M70 mixes, respectively. The M70 grade SCC with AGMS shows the highest resistance to acid attack with 2.54% and 5.50 % weight loss and 3.41% and 6.59 % strength loss for 2% and 5% dilution respectively. The M20 grade SCC with RS shows the least resistance to sulphate attack with 4.43% weight loss and 10.85 % strength loss, while M70 grade SCC with AGMS shows the highest resistance to sulphate attack with 1.06% weight loss and 1.66 % strength loss. Across all SCC grades, AGMS reduced water absorption, porosity, permeability, and charge passed by 40%, 37%, 36%, and 33%, respectively, while WGMS achieved reductions of 20%, 18%, 31%, and 21%, relative to RS. This research concludes that the appropriate selection and grading of M-sand are critical to achieving high-strength, durable SCC.

1. Introduction

Self-compacting concrete (SCC) and manufactured sand (M-sand) have revolutionized modern construction practices, offering sustainable, efficient, and high-performance alternatives to conventional methods and materials [1-2]. As the construction industry grapples with increasing demands for quality, speed, and environmental responsibility, the integration of these advanced technologies has become essential [3]. This paper explores the applications of M-sand in self-compacting concrete, aiming to highlight its contributions to civil engineering.

Manufactured sand is obtained from crushing granite or basalt hard stones to create an artificial variant of river sand [4]. The process of river sand extraction causes ecological problems as well as destroys river beds [5]. Proper selection of river sand becomes crucial for using it in self-compacting concrete because this material contains silt and clay along with organic impurities. M-

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sand is produced in controlled facilities to achieve regular grain distribution without organic contaminants. The incorporation of M-sand helps resolve both environmental issues linked to river sand mining and equipment shortages for natural sand resources [6]. M-sand production requires multiple crushing phases followed by screening procedures to guarantee continuous high-quality and correct particle dimension control [7].

Managing the fractions falling below 150 microns represents a major challenge during M-sand production [8]. Extensive amount of fine particle leads to several production issues such as inadequately increased water usage and decreased workability of products which subsequently weakens concrete mixes. Industrial plants use grading methods to handle and separate their fines components for resolving this issue. Wet grading and air grading represent the basic methods which producers currently use for material separation [8]. The production of precise particle size distribution in air-graded M-sand (AGMS) depends on using air separators. The air grading system introduces crushed sand to a chamber where high-speed air streams split the finer components based on density and size and form from the larger particles. The process of grading separates fines as light material at the chamber top from heavier materials at the bottom to gather M-sand into a single group [9]. This technique provides environmental benefits through its closed operating system that reduces water pollutants while also conserving water resources since water is not essential for separation. Continuous check and adjustment of fines content becomes possible through air grading which ensures constant purity levels [9]. The wet-graded M-sand (WGMS) performs particle and contaminant elimination through water-based separation techniques. M-sand manufactured through wet grading produces high-quality material of low silt-clay content, nevertheless, this approach necessitates a dependable water source as well as appropriate wastewater and silt disposal management. The choice between air-graded M-sand and wet-graded M-sand depends on different factors such as water supply conditions and environmental standards along with outcome quality expectations. The technique of wet grading remains widespread in regions with ample water supply. Air grading offers superior options in water-scarce areas and strict environmental restrictions.

The utilization of M-sand in self-compacting concrete provides several performance-based as well as sustainability-oriented advantages. Studies shows that M-sand used along with 0 -15% of silica fume improves the rheological and mechanical properties of SCC [10]. The SCC mixes with recycled coarse aggregate (RCA) showed improved strength when M-sand was used as partial replacement for fine aggregate, also the SEM indicated that cracks and voids in RCA were better filled with M-sand thereby improving the interfacial transition zone (ITZ) [11]. The optimal replacement level for achieving higher strength and durability in SCC was found to be 50% [12]. It was observed that addition of M-sand and fly ash, improved the fresh properties, compressive strength and split tensile strength of SCC while the flexural strength remained constant [13]. The passing ratio of L-box test increased by 21%, the blocking ration in J-ring test increased by 25% and the compressive strength increased by 19% for 100% M-sand in SCC [14]. M-sand was found to result in lower flowability but higher mechanical properties in SCC compared to dune sand [15]. To achieve the desired flowability, a higher paste volume was required compared to SCC with river sand [16]. SCC with quarry dust showed improved performance in fresh state and the mechanical strength of concrete was also observed to increase up to 30% replacement of river sand with quarry dust [17]. SCC with 100% M-sand as replacement for river sand and 30% fly ash showed satisfactory flowability, passing ability and segregation resistance [18]. Shrinkage parameters were the least for conventional concrete made by 20% silica fume as replacement for cement and 60 % replacement of river sand by M-sand [19]. The load-carrying capacity of self-compacting concrete with coconut shell increased by 22% when M-sand was used as replacement for river sand [20]. SCC with manufactured sand possesses higher pumpability and better air content than with river sand, due to better angularity of M-sand particles and presence of stone powder [21].

This research examines how M-sand in SCC contributes to building innovations through comprehensive examination of manufacturing strategies and categorization methods and practical industry applications. This study evaluates the influence of river sand (RS), air graded M-sand (AGMS) and (WGMS) on the mechanical, durability properties and bond behavior of SCC. The building industry currently requires detailed research on M-sand as a replacement of natural river sand because of escalating environmental problems, increasing construction expenses and declining material availability and supply. This evaluation examines mechanical strength and durability features of river sand in comparison to AGMS and WGMS across concrete grades M20, M40 and M70.

2. Materials and Methods

Self-compacting concrete with grades M20, M40 and M70 has been designed based on Indian standards to perform this experimental investigation. The experimental analysis uses materials listed below with their appropriate properties.

2.1. Cement

The experimental research utilizes 53-grade ordinary portal cement having 3.07 specific gravity that meets IS specifications for binder applications.

Table 1. Physical Properties of Cement

Properties	Observed Value	Permissible Value as per IS: 12269-2013 [22]
Fineness (Blaine's Air Permeability method)	281 m^2/kg	225 m^2/kg (minimum)
Fineness of Cement (retained on 90µ sieve)	2.5%	Less than 10%
Normal Consistency	32%	-
Specific Gravity	3.07	-
Initial Setting Time	120 min	30 min (minimum)
Final Setting Time	475 min	600 min(maximum)
Soundness test	1 mm	10 mm (maximum)
Le-chat expansion (Auto clave %)	0.09%	0.8 % (maximum)
Compressive strength of mortar cubes		
3 days	28.50 N/mm^2	27 N/mm^2 (minimum)
7 days	39.00 N/mm^2	37 N/mm^2 (minimum)
28 days	56.53 N/mm^2	53 N/mm^2 (minimum)

2.2. Fly Ash

The experimental work utilized class 'F' fly ash from Raichur thermal power plant which has a determined specific gravity of 2.4 for this project.

Table 2. Chemical and Physical Properties of fly ash

Chemical Properties		Physical Properties	
Oxide	Content (%)	Property	Value
SiO_2	58.76	Fineness (Blaine's permeability) (m2/kg)	330
Al_2O_3	31.48	Particles retained ON 45 micron IS sieve (%)	30
Fe_2O_3	2.85	28 days compressive strength (N/mm2)	44
CaO	0.75	Soundness (mm)	1.2
MgO	0.85	Specific Gravity	2.4
SO_3	0.01	Color	Light grey
Loss on Ignition (%)	0.81		

2.3. Fine Aggregates

2.3.1 Natural River Sand

The natural river sand that was locally procured adhering to the specifications for fine concrete aggregates in IS: 383:2016 [23] having calculated specific gravity of 2.56 was used after sieving to ensure uniform grading and size distribution.

2.3.2 Manufactured Sand

This research assessed two distinct methods of grading of M-sand as alternative fine aggregate - air grading or wet grading.

- Air-graded M-sand (AGMS) is separated using a dry air grading process, which selectively removes excess fines and ensures a well-graded particle size distribution. This process results in angular, rough-textured particles with improved packing density and inter-particle friction, traits that are particularly beneficial in enhancing the mechanical and rheological properties of self-compacting concrete. The specific gravity was found to be 2.65.
- Wet-graded M-sand (WGMS) was produced by washing and hydro-cycloning to remove fines and impurities. While this process also yields a clean product, it tends to retain slightly higher moisture content and a greater proportion of ultra-fine particles compared to air-graded M-sand. These characteristics can influence the water demand and workability of the resulting concrete mix. The specific gravity was found to be 2.39.

Both types of M-sand were used at varying replacement levels (0%, 25%, 50%, 75% & 100%) to evaluate their impact on the fresh, mechanical, and durability performance of SCC across M20, M40, and M70 grades. The consistent particle gradation and controlled production of manufactured sand provided a reliable basis for comparative assessment against natural river sand.

Table 3. Physical Properties of RS, AGMS & WGMS

Property	RS	AGMS	WGMS	Permissible limit (IS383:2016) [23]
Specific Gravity	2.56	2.65	2.39	2.1 – 3.2
Water Absorption (%)	1.78	0	3.54	<2% - RS <5% - M-sand
Fineness Modulus	2.92	2.71	2.66	2.2 – 3.2

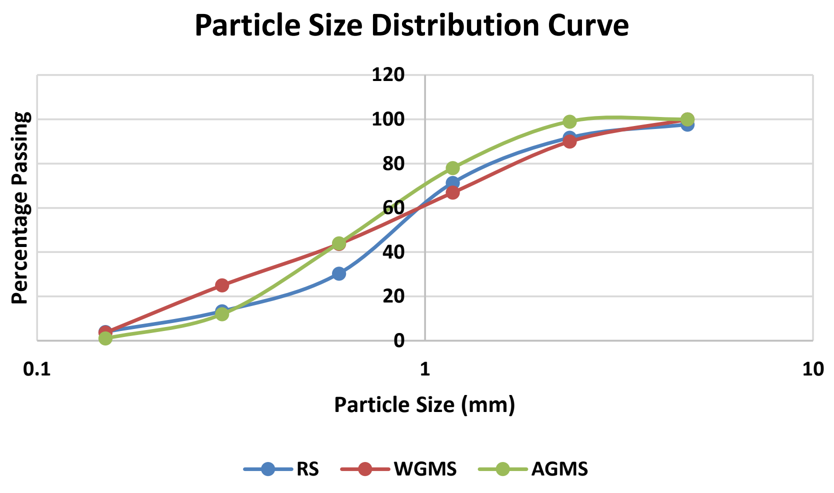

Fig. 1. PSD curve for fine aggregates

Fig 1. Illustrates the particle size distribution curve for all the three types of fine aggregates used in this study, from the PSD curve, it can be inferred that the gradation for river sand shows a more gradual increase in particle passing percentage, indicating a mix of fine and coarse particles. Air-graded M-Sand has the most uniform gradation, with a higher percentage passing in the mid-range sieves, indicating better grading control. While the Wet-graded M-Sand has a steeper curve in the middle range, meaning finer particles dominate compared to River Sand.

2.4. Coarse Aggregate

The aggregate was sourced from a local quarry and selected based on compliance with the specifications outlined in IS: 383–2016 [23]. The material exhibited a specific gravity of 2.63 thereby satisfying the expectations for high-quality coarse aggregates that can be used in structural concrete applications. Laboratory analysis showed that the aggregate had proper grading where each fraction measured between 10 mm and 20 mm in dimension.

Table 4. Physical properties of Coarse Aggregate

Properties	Results	Permissible limit (IS383:2016) [23]
Specific gravity	2.63	2.5-2.8
Bulk density (kg/m^3)	1590	1650
Aggregate impact value	12.52%	30
Aggregate crushing value	26.67%	30
Fineness modulus	6.37	6 – 7
Water absorption (%)	0.3	< 0.5%
Flakiness index	24.2	25%

2.5. Superplasticizer

Glenium Master Sky 8233 serves as the superplasticizer because its developers conceptualized it using advanced polycarboxylate ether (PCE) technology. The water reduction capability and sustained slump behavior of this material exists within 1.08 ± 0.02 specific gravity and pH range of 6-8.

2.6. Viscosity Modifying Agent

The rheological characteristics of self-compacting concrete experience a boost when using Glenium Stream 2 as a viscosity modifying agent (VMA) because it enhances mix cohesion while minimizing mix segregation and bleeding occurrences. The VMA maintains specific gravity at 1.01 ±0.01 together with pH value at 8 ± 1.

2.7. Methodology

The SCC mixes were developed following the compressive strength-based mix proportioning approach as per IS 10262:2019 [24] and IS 456:2000 [25], with adjustments made to meet the fresh property requirements outlined in the EFNARC guidelines [26] for SCC. The mix design targeted an M40 grade with a characteristic compressive strength (f_{ck}) of 40 MPa. A target mean strength of 48 MPa was adopted considering a suitable margin for variability. A total binder content of 450 kg/m^3 was selected within the recommended SCC range (430–520 kg/m^3), with 20% fly ash used as a mineral admixture (i.e., 360 kg cement + 90 kg fly ash). A water-to-binder ratio of 0.35 was maintained to achieve the desired strength and workability.

Superplasticizer and Viscosity Modifying Agent (VMA) were incorporated at 1% and 0.2% of the total binder weight, respectively, based on product specifications and preliminary trials. Their specific gravities were considered to be 1.08 and 1.01 for volumetric calculations. The coarse aggregate volume fraction was limited to 0.45 of the total aggregate volume to enhance flowability, as recommended by EFNARC [26]. Based on volumetric calculations, the remaining volume was distributed between coarse and fine aggregates (45% and 55%, respectively). This yielded 807.94 kg/m^3 of coarse aggregate and 960.98 kg/m^3 of river sand (for the 0% M-sand control mix). The design process included validation through trial mixes, assessing key SCC properties such as slump flow, V-funnel time, L-box ratio, and segregation resistance, to ensure compliance with EFNARC's performance criteria.

Table 5. Mix proportion for M20, M40 and M70 grade SCC with RS, AGMS and WGMS

Conc. Grade	Mix	Cement (kg/m³)	Fly Ash (kg/m³)	Water (kg/m³)	CA (kg/m³)	River Sand (kg/m³)	Admixture (kg/m³)	M-Sand (kg/m³)
M20 – Ordinary Strength Self-Compacting Concrete	RS100/20	320	80	180	802	955	4.0	0
	AGMS25/20	320	80	180	802	716	4.0	248
	AGMS50/20	320	80	180	802	477	4.0	496
	AGMS75/20	320	80	180	802	239	4.0	744
	AGMS100/20	320	80	180	802	0	4.0	993
	WGMS25/20	320	80	180	802	716	4.0	223
	WGMS50/20	320	80	180	802	477	4.0	446
	WGMS75/20	320	80	180	802	239	4.0	669
	WGMS100/20	320	80	180	802	0	4.0	892
M40 – Medium Strength Self-Compacting Concrete	RS100/40	360	90	158	808	961	4.5	0
	AGMS25/40	360	90	158	808	720	4.5	248
	AGMS50/40	360	90	158	808	480	4.5	497
	AGMS75/40	360	90	158	808	240	4.5	746
	AGMS100/40	360	90	158	808	0	4.5	995
	WGMS25/40	360	90	158	808	720	4.5	224
	WGMS50/40	360	90	158	808	480	4.5	449
	WGMS75/40	360	90	158	808	240	4.5	673
	WGMS100/40	360	90	158	808	0	4.5	897
M70 – High Strength Self-Compacting Concrete	RS100/70	400	100	145	710	1036	7.5	0
	AGMS25/70	400	100	145	710	777	7.5	268
	AGMS50/70	400	100	145	710	518	7.5	536
	AGMS75/70	400	100	145	710	259	7.5	805
	AGMS100/70	400	100	145	710	0	7.5	1073
	WGMS25/70	400	100	145	710	777	7.5	242
	WGMS50/70	400	100	145	710	518	7.5	484
	WGMS75/70	400	100	145	710	259	7.5	726
	WGMS100/70	400	100	145	710	0	7.5	967

(a)

(b)

Fig. 2. (a) Casting of specimen (b) mixing of concrete

A total of 9 mixes were prepared for each grade as shown in Table 5, the mix RS100/20 can be read as M20 grade mix with 100% river sand (control mix), the mix AGMS25/20 refers to M20 grade concrete with 25% AGMS, the mix WGMS25/20 refers to M20 grade concrete with 25% WGMS and so on. The mixing was done using a PAN mixer, for the first 30 seconds, fine aggregate and coarse aggregates were mixed after which half the quantity of water was added. The mixing continued for another 60 seconds till the aggregates absorbed the water, after this the powder content including cement and fly ash were added to the mixer and mixed for 60 seconds, at this stage the superplasticizer and VMA mixed with remaining water were added to the mixer and the entire mix was mixed for 180 seconds.

2.7.1 Fresh Properties

- Slump Flow Test

The slump flow test is one of the most widely used methods for evaluating the fluidity and filling capacity of concrete. Its simplicity and ease of application make it suitable for both laboratory and field conditions. In this test, an Abrams cone is placed on a non-absorptive surface and filled with fresh concrete without compaction. Upon lifting the cone, the concrete spreads under its own weight. The maximum diameter of the spread is measured in two perpendicular directions, and the average value is recorded. Additionally, the *T50 flow time*, which represents the time taken for the concrete to spread to a 50 cm diameter, is documented. IS 10262:2019 [24] provides guidelines on the typical range of slump flow values and their applications in concrete mix design.

- V-Funnel Test

The viscosity of self-compacting concrete (SCC) is evaluated using the V-funnel test, as specified in IS 1199 (Part 6) [27]. This test measures the time required for fresh concrete to flow through a V-shaped funnel, known as the *V-funnel flow time*. Concrete with lower viscosity exhibits a rapid initial flow before stopping, while higher-viscosity concrete may continue flowing gradually over time.
Based on flow time, viscosity is categorized into two classes: V1 and V2. V1-class concrete has superior filling ability, making it suitable for applications with congested reinforcement. It also exhibits self-levelling properties and provides an excellent surface finish. V2-class concrete, while beneficial in reducing formwork pressure and improving segregation resistance, may be prone to thixotropic effects, affecting surface finish and workability during placement.
The flow time for V1-class concrete should not exceed 8 seconds, whereas for V2-class concrete, it ranges between 8 and 25 seconds. A longer flow time indicates higher internal friction and lower flowability, while a very short flow time may suggest poor mix stability due to excessively low viscosity.

- L-box Test

The L-box test is conducted to evaluate the passing ability of self-compacting concrete (SCC). This test measures the concrete's ability to flow through confined spaces, such as reinforcement, without segregation or blocking. The minimum acceptable ratio of concrete depth in the horizontal section to that in the vertical section is 0.8, while a ratio of 1.0 indicates unrestricted flow, similar to that of water.

(a) (b)

Fig. 3. (a) L-Box test (b) V-Funnel test

In this test, fresh concrete is placed in the vertical section of the L-box and allowed to rest for 60 seconds to account for potential segregation. Upon opening the gate, the concrete flows into the horizontal section, where rebar obstructions may be included to simulate reinforcement congestion. The parameters recorded include the descent of the sample head (*Ha*), which reflects the blocking tendency, the final depth at the far end (*Hi*), representing filling ability, and the time taken for the concrete to reach a specified flow distance, indicating its deformability.

According to EFNARC guidelines [26], the blocking ratio (*Ha/Hi*) is used to assess the mix's passing ability, with an acceptable range between 0.80 and 1.0.

2.7.2 Mechanical Properties

- Compressive Strength

The compressive strength test is a key indicator of concrete quality, providing insight into its overall performance. The test included casting of around 270 cubical specimen of 150 mm size in accordance with IS 516:1959 [28], for each mix proportion at a total of 10 specimen were cast and tested and their average values were recorded. The cubes were removed from the mold after 48 hours and cured for a period of 28 days, before testing them under compression testing machine.

- Tensile Strength

The split tensile strength test is a reliable means of assessing concrete tensile failure resistance in structural members being subjected to tensile failure. It is an indirect method for determining concrete tensile capacity by the split tensile strength test conducted in adherence to IS 516:1959 [28]. In this test, a cylindrical specimen with 300 mm x 150 mm dimensions is loaded axially in compression where tensile stresses are generated perpendicular to the impact force. For this test a total of 270 cylindrical specimen, were cast and tested. For each mix proportion 10 specimen were tested and their average values were recorded. It is one of the important tests which are used to assess concrete durability, predict cracking behavior and enhance structural resilience.

(a) (b)

Fig. 4. (a) Compressive strength test (b) Split Tensile Strength

2.7.3 Durability Properties

- Water Absorption

A total of 270 cubical specimen (10 for each mix proportion) of 150 mm size were cast to determine saturated water absorption test at 56 days in accordance to ASTM C642 standards [29]. First of all, specimens were weighed in their initial state and then dried at 105°C for 24 hours in a hot air oven followed by drying until mass difference between two successive measurement made 24 hours apart was constant. After maintaining a constant dry weight, specimens were then cooled to room temperature and placed in potable water. At regular intervals, specimens were removed, surface dried over a clean cloth, and weighed. The specimen remained in this manner till it was saturated fully. All the specimen were then oven dried and the saturated weight was measured, calculation of the percentage water absorption from Eq. 1 was then conducted.

$$\%\ Water\ absorption = \frac{(Ws - Wd)}{Wd}\ x\ 100 \tag{1}$$

Where, W_s = weight of specimen at fully saturated condition, and W_d = weight of oven dried specimen.

- Porosity

Saturated water absorption is closely linked to the effective porosity, which quantifies the interconnected voids within the concrete matrix. Effective porosity (%) can be calculated using Eq. (2), after measuring the submerged weight of the specimen, in accordance to ASTM C642 standards [29].

$$Effective\ porosity,\ n = \frac{(w_s - w_d)}{(w_s - w_{sub})}\ x\ 100 \tag{2}$$

Where, W_{sub} = submerged weight of the specimen

- Rapid Chloride Penetration Test

The entry of chloride ions stands as a main factor that triggers reinforcing steel corrosion which results in damage to concrete structures such as bridges and parking lots as well as marine structures and industrial infrastructure. Millions of dollars annually represent the total repair expenses from corrosion damage. Uncracked concrete allows chlorides to enter through capillary absorption and hydrostatic pressure and diffusion and evaporative transport but diffusion shows the strongest effect. The migration of ions occurs from concrete interior to reinforcement when chloride concentration in the exterior surpasses the interior. These environmental conditions consisting of moisture and oxygen and cyclic wetting followed by drying processes speed up steel corrosion. The penetration speed of chloride depends on concrete pore structure that results from mix design and curing conditions and hydration and construction methods. Measuring chloride permeability requires 60V DC to flow through concrete samples with dimensions of 100 mm diameter and 50 mm thickness for a period of six hours with one end submerged in 0.3M NaOH and the other end in 3.0% NaCl solution as per ASTM C1202 [30]. The amount of electrical charge passed during testing enables reliable assessment of concrete permeability along with durability indicators. In this study a total of 45 specimen were tested and the results have been recorded and discussed.

- Water Permeability

The water permeability test is a critical assessment of concrete's durability, particularly its resistance to water ingress under pressure. This test provides insight into the pore structure and overall quality of the concrete matrix, which directly influences long-term performance in aggressive environmental conditions. For this study, a total of 108 concrete cubes of 150 mm size were used in accordance with DIN 1048 Part 5 [31], which outlines the procedure for determining the depth of water penetration under pressure. The test involves subjecting one face of the cube to water pressure (typically 5 bar) for a specified duration, after which the specimen is split to measure the maximum depth of water penetration. This method is widely accepted for evaluating the permeability and densification of concrete, especially in high-performance and self-compacting concretes.

- Acid Attack

Concrete is highly susceptible to acid attack due to its alkaline nature. When exposed to acidic environments, the cementitious matrix undergoes chemical disintegration, primarily through the dissolution of calcium hydroxide ($Ca\ (OH)_2$). The extent of degradation depends on concrete porosity, acid concentration, solubility of calcium salt, and the transport of acidic solutions through interconnected voids and cracks. Sulfuric acid (H_2SO_4) is particularly aggressive, as it induces both acidic and sulphate attacks, significantly compromising concrete integrity. Acidic solutions with $pH<7$ contain a high concentration of hydrogen ions (H^+), accelerating chemical degradation.

Groundwater contamination from industrial effluents containing sulfuric, hydrochloric, and nitric acids can severely impact concrete substructures, such as foundations, basements, and trenches. Additionally, marine environments and chemical storage structures are frequently exposed to aggressive acidic conditions, leading to progressive deterioration, loss of strength, and structural failure. The impact of acid attack was evaluated by immersing 162 concrete cubes of 150 mm size in 2% and 5% sulfuric acid (H_2SO_4) solution as per ASTM C1898 – 2000 [32]. Following acid exposure for 56 days, changes in weight and compressive strength were assessed to determine deterioration levels. This study provides insights into the resistance of concrete to acidic environments, which is crucial for ensuring the durability and service life of concrete structures in chemically aggressive conditions.

- Sulphate attack

Sulphate attack represents a major threat to concrete structures which exist in areas with sulphate presence from groundwater and soil or seawater. Sulphate materials originating from agricultural draining water and ocean water cause external sulphate attack on the structure. In sulphate-rich regions, such as coastal and semi-arid areas, effective mix design is essential for durability. To evaluate sulphate resistance, 81 number of concrete cubes of 150 m size, were first cured in water for 28 days, followed by 56 days of immersion in 5% magnesium sulphate ($MgSO_4$) solution as per ASTM C1898 – 2000 [32]. Changes in mass and compressive strength were analyzed to assess deterioration in comparison to water-cured specimens, providing insights into sulphate resistance in aggressive environments.

- Bond strength

The bond strength between concrete and reinforcement bars is a critical parameter influencing the structural performance and serviceability of reinforced concrete elements. The bond between concrete and reinforcement, ensures a composite action facilitating effective stress transfer and crack control under loading.

(a) (b) (c)

(d) (e) (f)

Fig. 5. (a) Curing of specimen (b) specimen for RCPT (c) specimen immersed in magnesium sulphate solution (d) specimen subjected to water permeability test (e) bond strength specimen (f) specimen after exposure to acid attack

The present study investigates the bond behavior of reinforcement bars of diameters 10 mm, 12 mm, 16 mm, 20 mm, and 25 mm embedded in 150 mm cubical specimen of SCC made with RS, AGMS and WGMS. A total of 45 specimen were cast and tested in accordance with IS:2770 (Part-I) [33]. The pull-out test method, a widely accepted technique for evaluating bond strength, is used to assess the interaction between the concrete matrix and the embedded steel bars. The test measures the maximum load resisted before slippage, offering insights into the adhesion, friction, and mechanical interlock characteristics governing bond performance. By varying the diameter of the reinforcement bars and the type of fine aggregate used in SCC, the study aims to identify trends and potential improvements in bond strength, with implications for the durability and efficiency of reinforced concrete structures.

3. Results and discussions

3.1. Slump Flow Test

The slump flow values for all mixes, ranging across M20, M40, and M70 grades incorporating various fine aggregate types, are shown in Fig. 6. As per EFNARC guidelines [26], self-compacting concrete should exhibit a slump flow in the range of 650–800 mm to ensure adequate filling ability without segregation. All the mixes tested fall within this permissible range, confirming their suitability as SCC.

Across all grades, AGMS consistently produced the highest slump flows, supporting its role in enhancing SCC workability. WGMS, while suitable, resulted in comparatively lower slump values, likely due to its higher angularity and less favorable gradation. River sand performed well but did not match AGMS in terms of flow enhancement, especially at higher grades.

All recorded values satisfy EFNARC criteria [26], validating the mix designs. The findings confirm that air-graded manufactured sand (AGMS) offers an optimal balance of grading, shape, and packing, making it a highly viable replacement for natural sand in SCC, especially when consistent workability is essential.

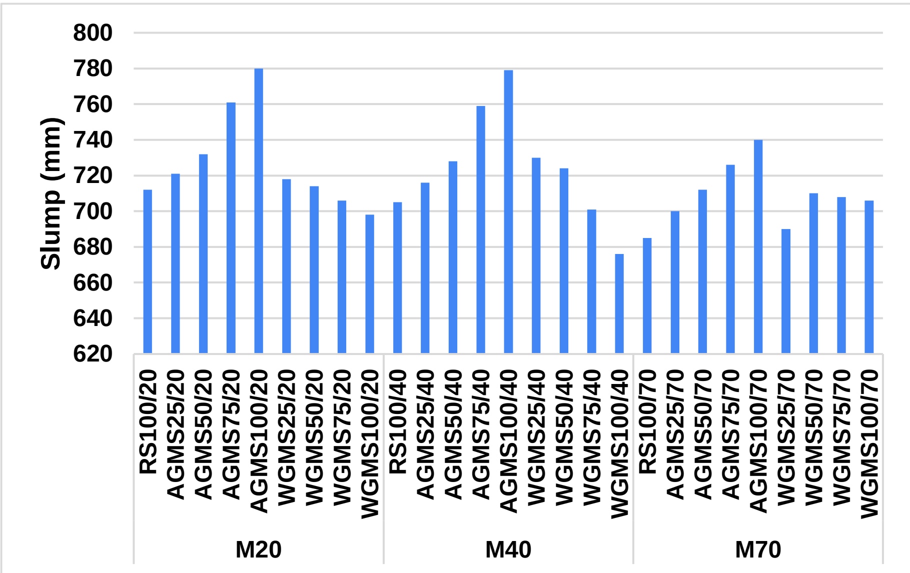

Fig. 6. Slump value for M20, M40 and M70 grade SCC using RS, AGMS ad WGMS

3.2. T50 Slump Flow Test

The T50 slump flow test provides insight into the viscosity and flow rate of self-compacting concrete (SCC). It measures the time (in seconds) taken for the concrete to spread to a 500 mm diameter during the slump flow test. As per EFNARC guidelines [26], acceptable T50 values for SCC typically range from 2 to 5 seconds, where lower times reflect faster flow (lower viscosity) and higher times indicate increased viscosity and resistance to flow. All mixes complied with EFNARC's

T50 limits (2–5 sec), indicating acceptable viscosity and suitability for SCC applications. AGMS at lower replacement levels consistently reduced T50 times, promoting faster flow and better placement ability. WGMS increased viscosity at higher replacement ratios, likely due to angularity and higher water demand. RS-based mixes demonstrated moderate and stable T50 times, serving as a benchmark for comparison. These results confirm that the type and proportion of fine aggregates significantly influence the flow rate and viscosity of SCC. AGMS, emerged as the most favorable for achieving a desirable balance between workability and flow resistance.

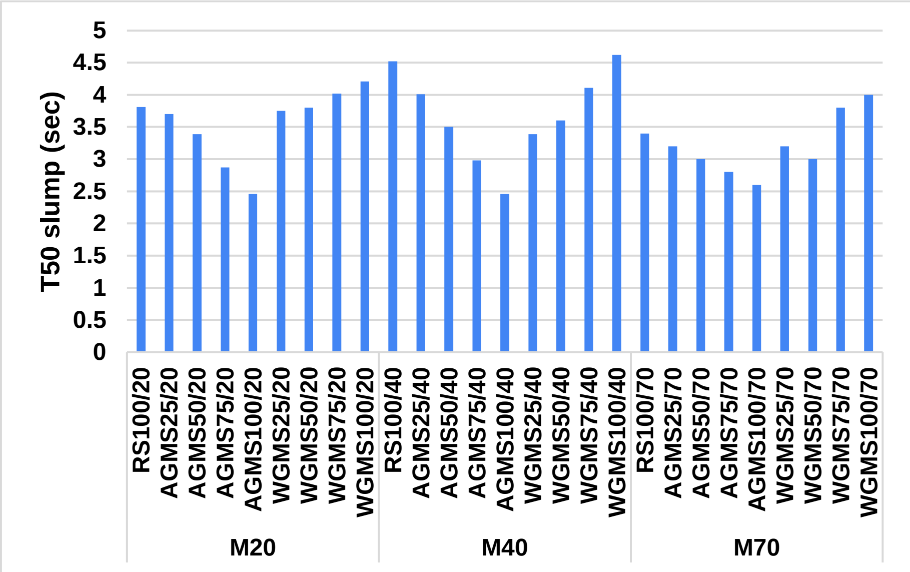

Fig. 7. T50 Slump for M20, M40 and M70 grade SCC using RS, AGMS ad WGMS

3.3. V-Funnel Test

The V-funnel test measures the viscosity and filling ability of SCC, with flow times between 6 to 12 seconds considered satisfactory as per EFNARC guidelines [26]. Higher values indicate greater viscosity and potential risk of blockage, while lower values suggest better flowability. Across all grades, SCC with AGMS recorded the lowest flow time, indicating enhanced flow due to improved particle packing. In contrast, SCC with 75% WGMS showed longer flow times, reflecting increased viscosity at higher replacement levels indicating slightly higher resistance to flow. These findings highlight the influence of sand type and replacement level on the viscosity of SCC, with AGMS mixes offering an optimal balance between flowability and stability.

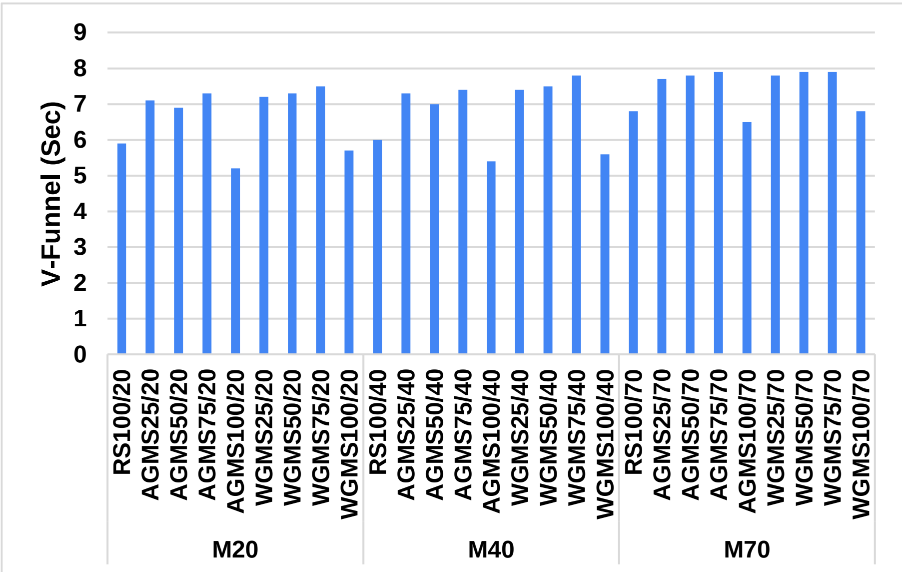

Fig. 8. V-Funnel test for M20, M40 and M70 grade SCC using RS, AGMS ad WGMS

3.4. L-Box Ratio

The L-box test evaluates the passing ability of self-compacting concrete, crucial in determining its suitability for heavily reinforced sections. According to EFNARC [26] and IS: 10262-2019 [24] recommendations, an L-box ratio (H2/H1) between 0.8 and 1.0 is considered acceptable for SCC, indicating good passing ability without segregation or blockage. Across all the grades of SCC, all variants, including those with RS, AGMS, and WGMS, showed L-box ratios between 0.80 and 0.95, fulfilling standard limits. Mixes with AGMS exhibited slightly higher ratios, indicating superior passing ability, likely due to better grading and particle shape compared to RS and WGMS. Overall, the results affirm that replacement of RS with AGMS offers enhanced passing ability while maintaining compliance with SCC workability criteria. WGMS, although viable, may require finer tuning of mix proportions or the use of viscosity modifying admixtures (VMAs) at higher replacement levels to match the performance of AGMS.

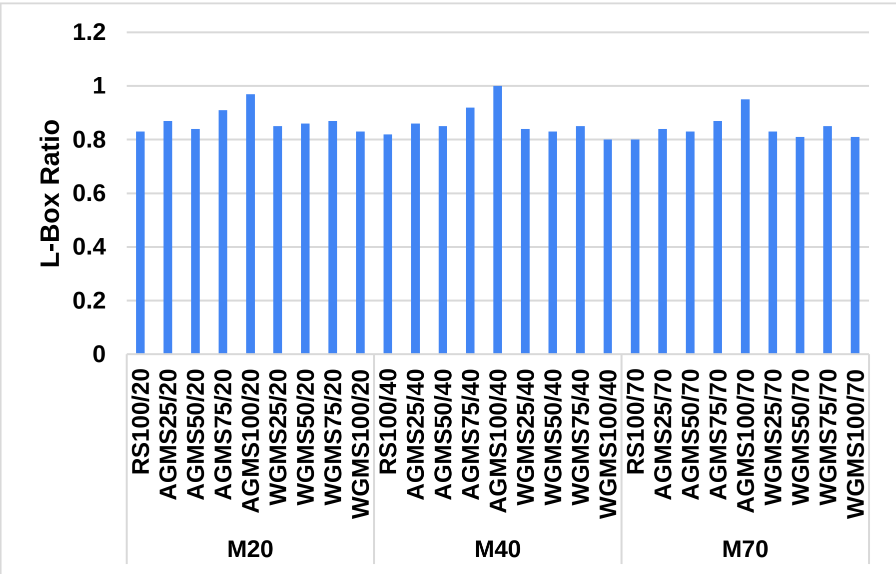

Fig. 9. L-Box Ratio for M20, M40 and M70 grade SCC using RS, AGMS ad WGMS

3.5. Compressive Strength

The compressive strength of M20 grade concrete containing air-graded M-sand increases according to replacement percentage with the strongest results achieved from 100% replacement. An escalation of compressive strength appears across M40 grade concrete as the replacement percentages rise beyond 75% and reach 100%. According to M70 grade concrete results the compressive strength exhibits stable values and reaches its peak level at 100% replacement since air-graded sand functions effectively in high-strength SCC mixes. The strength measures for M20 grade concrete achieve higher values through M-sand replacement taking place by wet grading even though the collected data remains lower than the testing results from air grading.

The M40 grade concrete shows a steady strength growth but the growth rate remains lower when compared to air-graded sand. In M70 grade concrete, strength remains high across all replacement levels, with 100% replacement producing nearly equal strength as natural river sand, indicating the suitability of wet-graded sand for high-strength SCC. Air-graded sand shows a more pronounced increase in compressive strength across all replacement levels, particularly in medium- and high-strength SCC mixes. Wet-graded sand demonstrates a steady but slightly lower strength gain compared to air-graded sand, though it remains suitable for high-performance SCC applications. At higher replacement percentages (75% and 100%), both sands yield comparable results in high-strength mixes (M70), confirming the viability of manufactured sand as a sustainable alternative to river sand. The compressive strength of SCC improves with increasing replacement of river sand with manufactured sand, with air-graded sand demonstrating a greater strength enhancement compared to wet-graded sand. In high-strength SCC (M70), both types of manufactured sand perform effectively, making them suitable replacements for river sand. Proper mix design adjustments are necessary to optimize the use of manufactured sand in different strength grades of SCC.

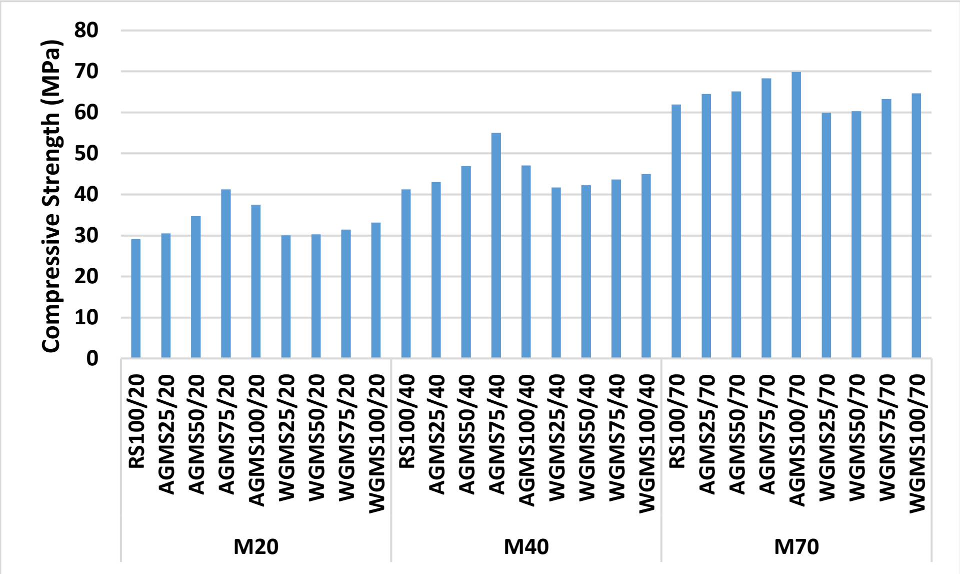

Fig. 10. Compressive Strength of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

3.6. Split Tensile Strength

The Tensile Strength Test was conducted on Self-Compacting Concrete (SCC) incorporating air-graded and wet-graded manufactured sand as a partial and full replacement for river sand. The analysis covers different mix grades: M20, M40, and M70, with replacement percentages of 0%, 25%, 50%, 75%, and 100%. Tests indicate that tension strength progressively rises as replacement levels increase in M20 grade concrete with air-graded M-sand reaching its maximum at full substitution. M40 grade concrete tests revealed that tensile properties increase when more replacement occurs until maximum values occur at total replacement of standard sand by air-graded sand. The effectiveness of air-graded sand for high-strength SCC remains high in M70 grade concrete because tensile strength remains consistent between 75% and 100% replacement levels.

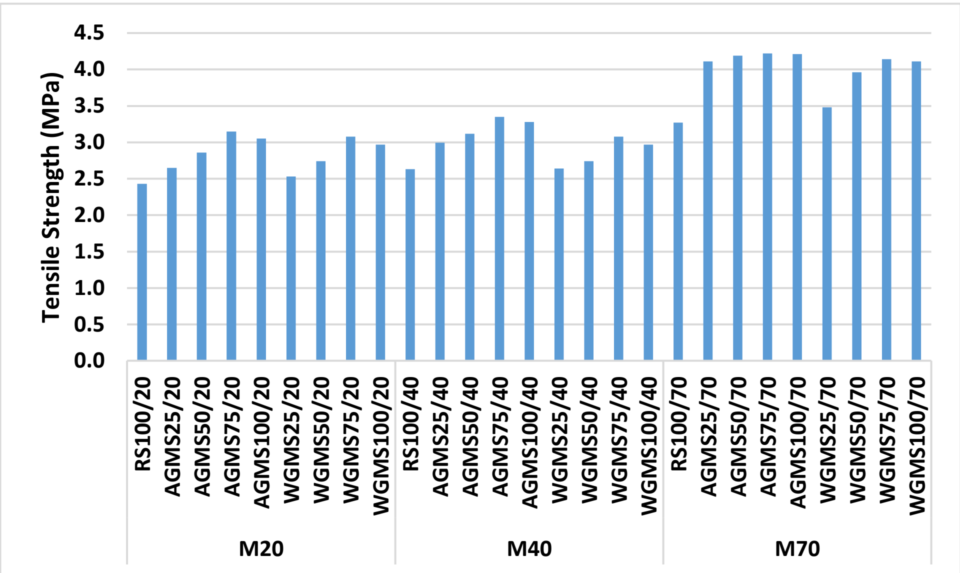

Fig. 11. Tensile Strength of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

Wet-graded M-sand used to make M20 grade concrete leads to rising strength values at each replacement fraction yet produces weaker outcomes than air-graded sand. The strength values in M40 grade concrete show a growing trend until they reach substantial heights starting at a 50% replacement threshold. When used as a substitute in M70 grade concrete the measurements of tensile strength match those from air-graded sand particularly at 75% and 100% replacement levels which establishes its use for high-strength SCC applications.

Air-graded sand exhibits a more pronounced increase in tensile strength across all replacement levels, particularly in medium- and high-strength SCC mixes. Wet-graded sand shows a steady but slightly lower strength gain, though at higher grades (M70), both sands yield nearly identical performance. At 100% replacement, both types of sand achieve optimal tensile strength, demonstrating their potential as sustainable alternatives to river sand. The tensile strength of SCC increases with the replacement of river sand by manufactured sand, with air-graded sand demonstrating slightly superior strength properties compared to wet-graded sand. However, both sands perform effectively at higher grades (M70), making them viable options for SCC production. The results indicate that manufactured sand can be a sustainable substitute for river sand, provided proper mix proportioning and quality control measures are implemented.

3.7. Water Absorption

The water absorption in SCC with air-graded M-sand remains the lowest when compared to the other three sand options. The concrete grade shows a direct correlation with decreasing values of water absorption. Better packing of particles along with decreased porosity characterizes the SCC material according to the lower water absorption readings. The water absorption levels in SCC that uses wet-graded M-sand exceed the values from air-graded M-sand while remaining under river sand absorption. Water absorption shows a declining behavior when concrete grades become higher. Water adsorption levels of air-graded sand are less than those of air-graded sand because of the distinct surface characteristics along with shape.

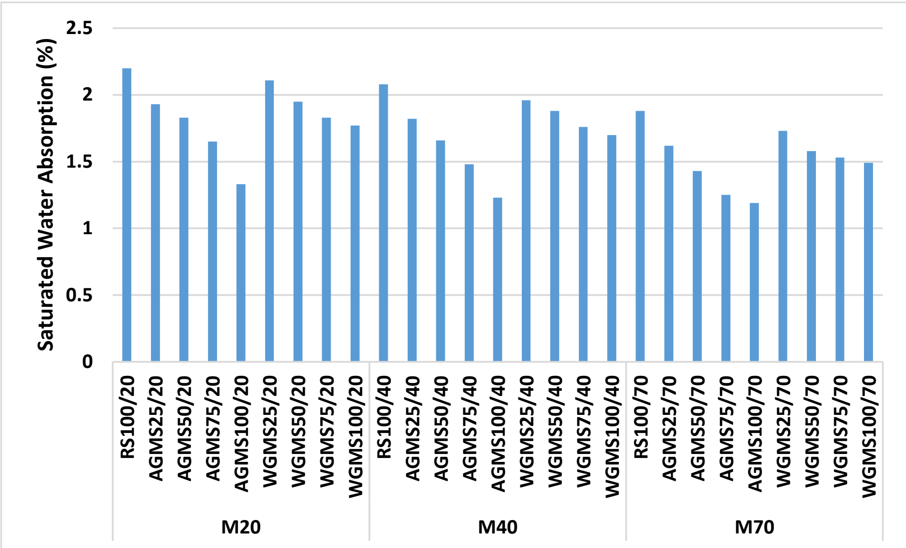

Fig. 12. Water Absorption of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

The highest amount of water absorption exists in SCC manufactured with river sand throughout all concrete grades. Higher absorption values demonstrate both increased material porosity and higher water requirement and could possibly degrade mix workability. The water absorption capability of manufactured sand (whether air-graded or wet-graded) proves to be lower than river sand because manufactured sand shows denser particle packing structures that result in lower porosity in SCC. Air-graded M-sand demonstrates the most efficient water absorption capability because its surface appears smooth and features optimal gradation thus improving the durability of SCC. Wet-graded M-sand has acceptable water absorption levels that open doors to becoming an adequate river sand replacement if mix ratios are adjusted correctly. The water-absorption capabilities decrease as concrete grade levels increase from M20 to M70 because higher-strength mixes maintain better compaction and possess fewer voids. Air-graded manufactured sand demonstrates maximum efficiency in replacing river sand as an SCC component while wet-graded sand remains a viable alternative for river sand substitution.

3.8. Porosity

Air-graded M-sand concrete exhibits the most compact porosity than any other sand type. Concrete grade has a direct relation to lower porosity values in the material structure. Better durability results from the denser microstructure which achieves optimal particle packing. The porosity of concrete made with wet-graded M-sand demonstrates slightly higher results than air-graded M-sand but remains lower than river sand. The concrete grade increase leads to decreasing values in the examinations. Drastic reduction in porosity exists at higher concrete strengths because it indicates improved aggregate compaction and better contact between aggregates. Steel-fiber-reinforced concrete with river sand possesses the largest interconnected void spaces when comparing all strength levels. Additional voids in SCC affect the durability and strength potential negatively. The low porosity results achieved by air-graded M-sand demonstrates the effectiveness of its better gradation and shape characteristics along with packing efficiency for enhancing SCC mechanical properties. The porosity results of wet-graded M-sand suggest it can replace river sand in concrete as long as the concrete mixture requires small changes during design. The highest porosity observed in river sand leads to inferior SCC durability because of increased permeability. Higher concrete grades lead to lower porosity values that result in better compacted denser concrete because of strong aggregate bonding. The most potent approach to reduce porosity involves air-graded M-sand followed by wet-graded M-sand which makes them suitable alternative options to river sand in SCC applications.

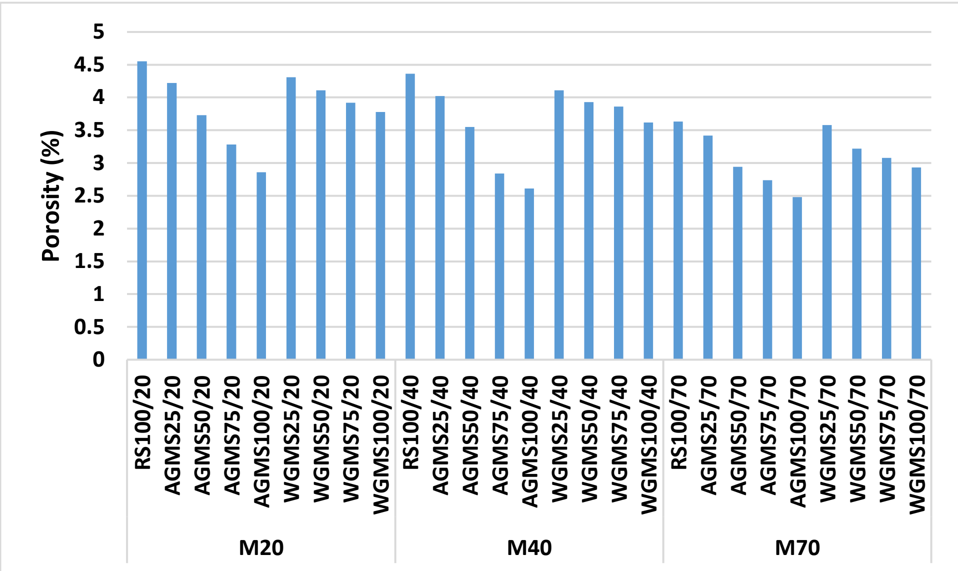

Fig. 13. Porosity of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

3.9. Rapid Chloride Penetration Test

A consistent trend is observed across all grades: as the percentage replacement of river sand with either AGMS or WGMS increases, the charge passed tends to decrease, indicating reduced chloride ion permeability and, consequently, improved durability. This trend is more pronounced in higher-grade mixes, where the total charge passed significantly reduces with increased substitution of natural sand, especially with AGMS.

In the M20 grade mixes, the SCC with 100% river sand exhibits the highest charge passed, exceeding 2400 Coulombs, indicative of high permeability. However, with a complete replacement using AGMS, the charge passed reduces to below 1500 Coulombs, marking a transition from high to moderate permeability. The effect of WGMS replacement is also beneficial, though slightly less effective than AGMS, with the charge passed nearing 1600-1700 Coulombs at 100% replacement.

In M40 SCC, the mix AGMS100/40 brings the charge passed well below 1200 Coulombs, falling within the low permeability category. WGMS also shows consistent improvement over river sand, although its performance remains marginally inferior to AGMS at each replacement level.

The M70 mixes demonstrate superior performance overall. Even at 100% river sand, the charge passed remains within a relatively low range, suggesting that the dense matrix of high-grade SCC inherently contributes to reduced permeability. However, with increasing proportions of WGMS and AGMS, particularly at 100%, the charge passed dips below 1000 Coulombs, indicating very low permeability. AGMS again shows marginally better performance than WGMS, reinforcing its suitability as a sustainable and durable replacement for river sand.

Overall, the study illustrates that both air-graded and wet-graded manufactured sands significantly enhance the resistance of SCC to chloride ion penetration across all strength grades. AGMS demonstrates superior performance, likely due to better particle grading and reduced fines content, which contribute to a denser microstructure. This finding supports the potential of AGMS and WGMS as effective alternatives to river sand, aligning with sustainability and durability requirements in modern concrete design.

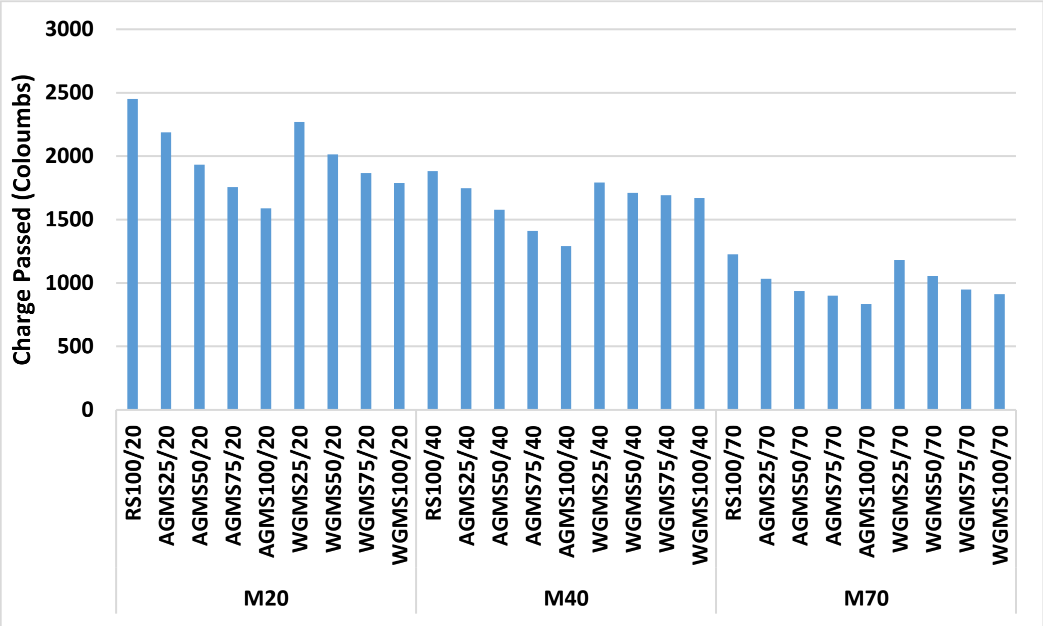

Fig. 14. RCPT values of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

3.10. Water Permeability

The graph presents the water permeability depth (mm) of self-compacting concrete (SCC) of varying grades (M20, M40, M70) incorporating RS, AGMS, and WGMS. The results indicate a clear trend of decreasing water permeability with the incorporation of AGMS and WGMS, in comparison to RS, across all concrete grades.

For M20 grade SCC, the highest permeability depth (~22 mm) is observed in the mix with RS100/20, indicating greater porosity and lower resistance to water penetration. Mixes incorporating AGMS and WGMS, particularly at higher replacement levels (AGMS100/20 and WGMS100/20), show a marked reduction in permeability, suggesting improved pore structure and densification. WGMS mixes, especially, exhibit the lowest permeability values in M20, implying enhanced microstructural refinement due to the finer and possibly more reactive ceramic particles.

In the case of M40 grade SCC, a general improvement in permeability resistance is observed compared to M20. RS100/40 again shows the highest water permeability (~21 mm), whereas mixes with AGMS and WGMS demonstrate significantly reduced permeability values.

WGMS100/40 shows a permeability depth below 15 mm, indicating superior durability characteristics. The results affirm that higher grade concretes benefit more from the inclusion of alternative sands, likely due to better matrix packing and pozzolanic activity.

For M70 grade SCC, the trend continues, with the lowest permeability values recorded overall. The RS100/70 mix still shows the highest permeability within the M70 series, but all AGMS and WGMS mixes display further reduction, with WGMS100/70 achieving the lowest value (~12 mm). This suggests that the ultra-high strength matrix of M70 enhances the benefits offered by ceramic sand incorporation, leading to denser, less permeable concrete.

Overall, the data clearly supports the assertion that substituting RS with AGMS and WGMS significantly improves water impermeability in SCC, particularly at higher grades and higher replacement levels. WGMS consistently outperforms AGMS and RS, indicating its potential as a sustainable and performance-enhancing fine aggregate in durable SCC production.

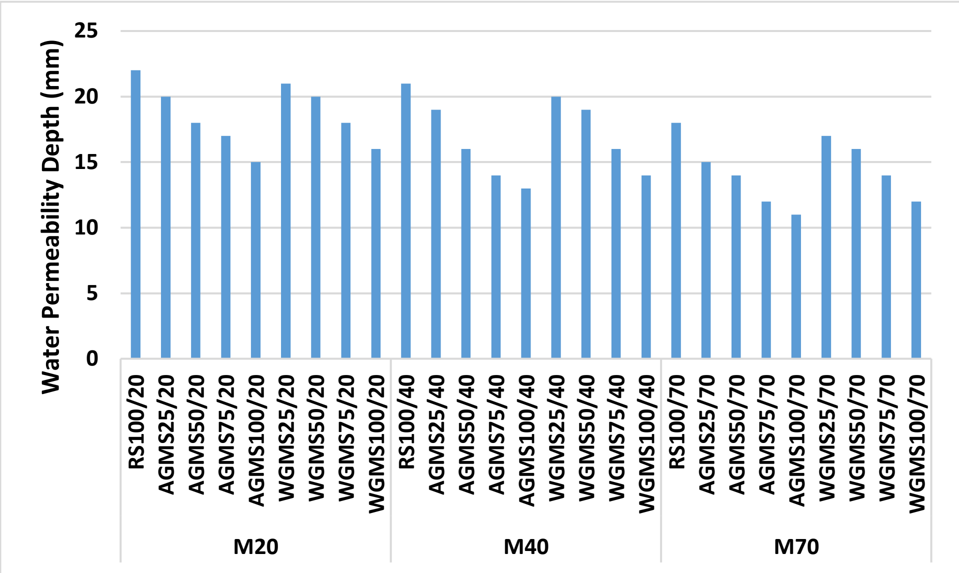

Fig. 15. Water Permeability Depth of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

3.11. Acid Attack

The bar graphs depict the percentage loss in strength and weight of self-compacting concrete (SCC) subjected to sulfuric acid (H_2SO_4) attack at 2% and 5% dilution levels. The strength loss measurement revealed its highest value in RS-based concrete surpassed WGMS-based and AGMS-based SCC. Higher concrete grades went from M20 to M70 which improved the resistance to acid attack by causing reduced strength degradation. All mixes experienced higher strength deterioration when subjected to 5% acid dilution as opposed to 2% acid dilution. Among the different mixtures AGMS based SCC demonstrated maximum resistance to acid deterioration because of its reduced strength loss properties.

Weight loss data tracked strength loss patterns where RS had the highest amount of deterioration but AGMS demonstrated the least impact. The strength level of M70 SCC achieved higher acid resistance as validated by its minimal weight reduction. The 5% diluted acid solution caused stronger material degradation than the 2% diluted acid solution thus leading to increased weight loss. AGMS based SCC exhibits a lower weight loss ratio thus proving its capacity to withstand acid deterioration effectively. The strength reduction together with weight loss appear lower within concrete mixes containing AGMS thus demonstrating this material's proper application within harsh environments. Concrete of higher grade (M70) demonstrates improved durability through which it becomes the optimal solution for situations that tend to become acidic.

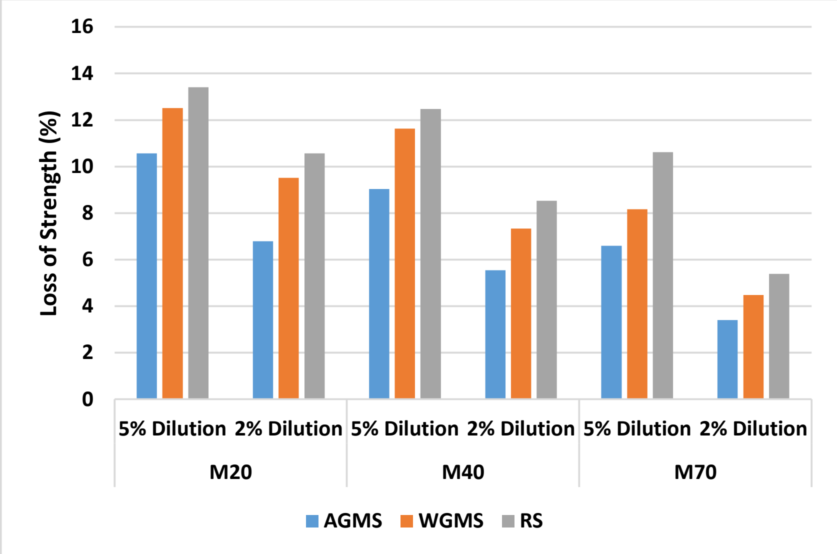

Fig. 16. Loss of strength due to acid attack of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

Table 6. Values of Initial and final weight and strength of acid attack

	Mix Proportions	Weight			Compressive Strength		
		Initial weight	Final Weight	Percentage Loss	Initial Strength	Final Strength	% Loss in Strength
5% Dilution of H_2SO_4	AGMS100/20	8.12	7.55	7.02	38.09	34.06	10.56
	WGMS100/20	7.53	6.85	9.07	33.32	29.15	12.51
	RS100/20	7.23	6.48	10.42	22.51	19.49	13.40
	AGMS100/40	8.19	7.67	6.35	46.97	42.73	9.04
	WGMS100/40	7.64	7.06	7.55	44.24	39.10	11.63
	RS100/40	7.41	6.79	8.37	32.23	28.20	12.48
	AGMS100/70	8.54	8.07	5.50	69.39	64.82	6.59
	WGMS100/70	8.23	7.65	6.97	64.14	58.90	8.17
	RS100/70	8.12	7.52	7.35	62.45	55.81	10.62
2% Dilution of H_2SO_4	AGMS100/20	8.12	7.78	4.27	38.09	35.50	6.79
	WGMS100/20	7.53	7.13	5.31	33.32	30.15	9.51
	RS100/20	7.23	6.78	6.22	22.51	20.13	10.57
	AGMS100/40	8.19	7.89	3.70	46.97	44.37	5.55
	WGMS100/40	7.64	7.27	4.84	44.24	41.00	7.33
	RS100/40	7.41	7.02	5.22	32.23	29.48	8.54
	AGMS100/70	8.54	8.32	2.54	69.39	67.03	3.41
	WGMS100/70	8.23	7.96	3.24	64.14	61.27	4.48
	RS100/70	8.12	7.73	4.80	62.45	59.08	5.39

The higher resistance to acid attack by SCC with AGMS may be due to its well-graded, angular, and rough-textured particles which enhances particle interlocking and paste-aggregate bonding, reducing capillary porosity. A denser microstructure minimizes acid ingress, which is key to resisting chemical attack. The specimens exhibited surface erosion, discoloration, and in some cases, softening of edges. Progressive exfoliation and minor surface pitting were evident. No deep or structural cracking was observed; however, micro-cracking was noticed in a few specimens upon close inspection.

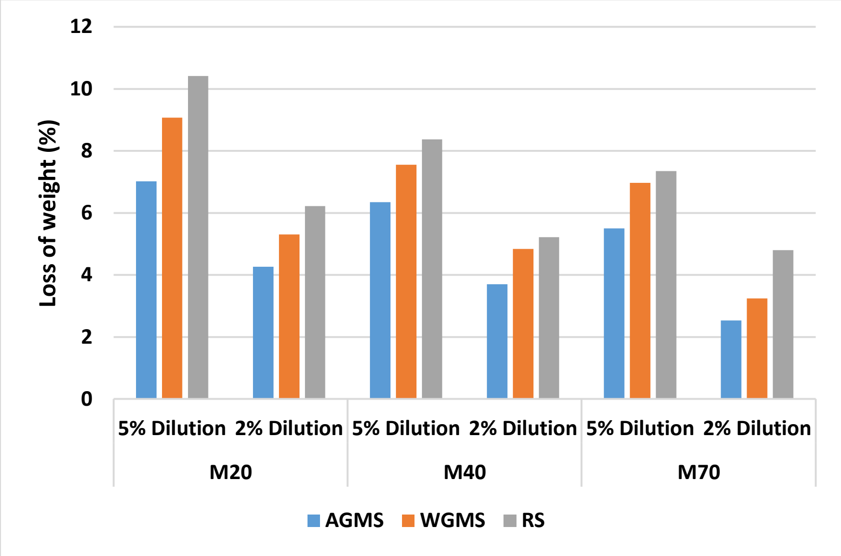

Fig. 17. Loss of weight due to acid attack of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

3.12. Sulphate Attack

The bar graph presents the percentage loss in strength and weight of self-compacting concrete (SCC) subjected to a 5% magnesium sulphate ($MgSO_4$) solution. The SCC containing river sand exhibited maximum weight loss which demonstrated its highest sensitivity to sulphate deterioration. AGMS-based SCC exhibited the minimum weight loss indicating strong sulphate resistance properties. Higher concrete strength levels resulted in better resistance towards sulphate attack which caused weight loss to decrease until the M70 grade exhibited the lowest level of degradation. SCC based on RS showed the maximum strength reduction among all three concrete types tested which was higher than both WGMS and AGMS based samples. Concrete containing AGMS developed minimum strength reduction which confirms AGMS as the most effective material for resisting sulphate attacks.

Table 7. Values of Initial and final weight and strength of sulphate attack

	Weight			Compressive Strength		
	Initial weight	Final Weight	Percentage Loss	Initial Strength	Final Strength	% Loss in Strength
AGMS100/20	8.13	7.93	2.42	37.37	36.08	3.45
WGMS100/20	7.52	7.21	4.17	33.92	32.23	4.98
RS100/20	7.23	6.91	4.43	23.28	20.76	10.85
AGMS100/40	8.19	8.07	1.51	46.97	45.58	2.97
WGMS100/40	7.76	7.52	3.09	44.07	42.38	3.82
RS100/40	7.23	6.96	3.78	31.90	29.16	8.58
AGMS100/70	8.52	8.43	1.06	69.01	67.87	1.66
WGMS100/70	8.22	8.06	1.87	64.71	62.85	2.87
RS100/70	8.13	7.93	2.54	62.12	58.30	6.14

The specimens subjected to sulphate exposure showed signs of surface scaling, minor cracking, and white crystalline deposits (efflorescence) due to sulphate salts. Slight swelling were observed, especially in mixes with higher water-cement ratios, though precise measurements were not taken in this study. Research outcomes demonstrate that specimens utilizing AGMS as a mix ingredient maintain superior magnesium sulphate resistance when compared to concrete made with WGMS and RS. This may be due to better particle packing resulting in a denser microstructure in AGMS as compared to WGMS and RS. The combination of higher concrete strength grades M70 leads to better resistance against sulphate attack since it exhibits minimal weight and strength deterioration. The utilization of AGMS as a component in SCC makes this concrete mixture a suitable choice for sulphate-rich areas because it produces outstanding deterioration reduction.

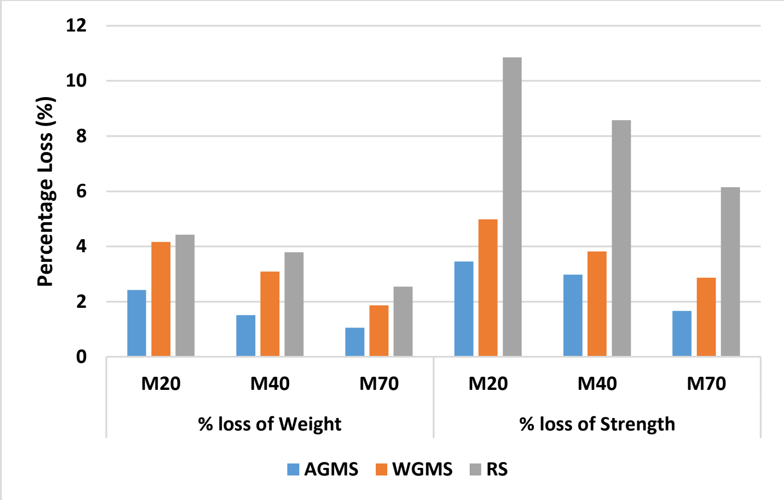

Fig. 18. Loss of weight and strength due to sulphate attack of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

3.13. Correlation Between RCPT, Water Absorption and Porosity

Fig 19. and Fig. 20. represent, MATLAB generated plots correlating Porosity vs RCPT and Water Absorption vs RCPT for M20, M40, and M70 SCC using 2nd-degree polynomial fits. For all grades, both porosity and water absorption exhibit a positive polynomial relationship with RCPT values. The use of a second-degree polynomial provides a superior fit over linear models, effectively capturing the curvature in the data at lower porosity or absorption levels where RCPT reduction becomes more gradual. In M20 SCC, A stronger curvature is observed in both WA–RCPT and PO–RCPT plots, higher water absorption and porosity correspond to significantly increased RCPT, indicating higher ion permeability, which implies that lower-grade SCC is more sensitive to microstructural changes. In M40 SCC, the correlation remains strong, with a clear parabolic relationship, both AGMS and WGMS series show similar trends, though WGMS tends to exhibit slightly higher RCPT for the same water absorption and porosity value. In M70 SCC, the plots show a flattening of the RCPT curve with decreasing water absorption and porosity, this grade demonstrates superior durability, as even marginal reductions in porosity lead to significant reductions in RCPT, the R^2 values are consistently high (exceeding 0.95), confirming the reliability of the polynomial fit. Both water absorption and porosity are indirect indicators of pore connectivity and permeability.

The strong correlation with RCPT demonstrates that reduced capillary porosity significantly impedes chloride ingress. The trend is more pronounced in AGMS, suggesting that the addition of active mineral constituents enhances durability more effectively than conventional methods. The method used for grading manufactured sand creates significant effects on the transportation behavior of SCC before it reaches its medium strength peak. Water absorption together with porosity measure RCPT performance well but processing methods applied to manufactured sand matter most for low-strength SCC concrete designs. The choice of sand for concrete construction requires thorough attention when durability is a key requirement in concrete mixtures with medium to low strength.

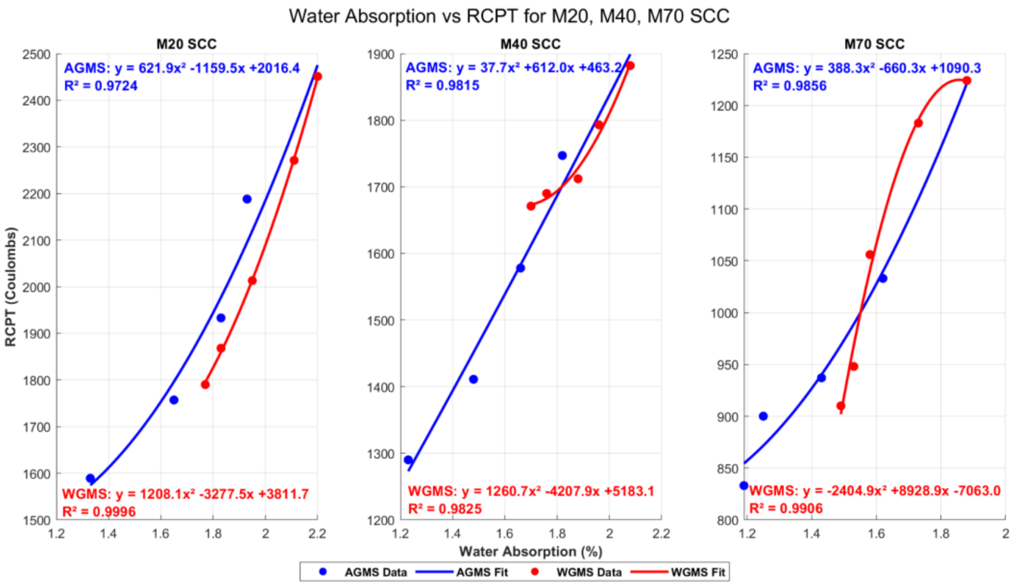

Fig. 19. Correlation between Water absorption- RCPT

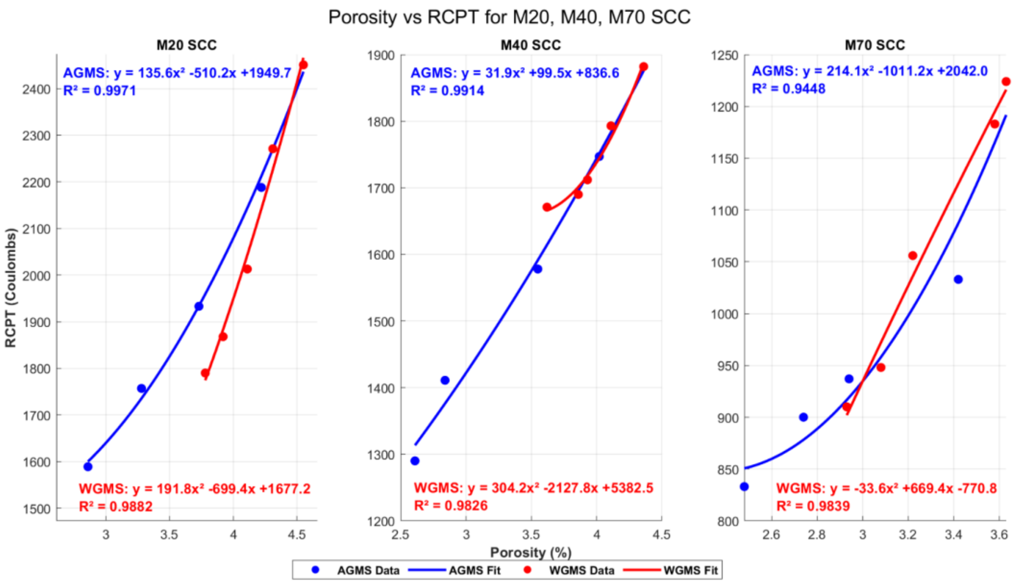

Fig. 20. Correlation between Porosity- RCPT

3.14. Bond Strength

The graph illustrates the variation in bond strength (MPa) of reinforcement bars with different diameters (10 mm, 12 mm, 16 mm, 20 mm, and 25 mm) embedded in SCC of grades M20, M40, and M70, using RS, AGMS, and WGMS. Across all concrete grades, AGMS consistently exhibits the highest bond strength for all bar diameters, indicating superior interfacial bonding between the reinforcement and the SCC matrix. This can be attributed to the angular and rough texture of AGMS, which enhances mechanical interlocking. Bond strength decreases with increasing bar diameter regardless of the concrete mix or sand type. This trend aligns with the principle that larger bars offer a lower surface area-to-volume ratio, reducing the effectiveness of the bond per unit area. With increasing concrete strength from M20 to M70, there is a noticeable improvement in bond strength for all sand types and bar sizes. This suggests that higher grade SCC provides a denser matrix, improving adhesion and confinement around the reinforcement. Among the sands, RS exhibits the lowest bond strength across all mixes and diameters, while WGMS shows intermediate performance, suggesting that although WGMS improves over RS, it does not outperform AGMS. The findings highlight that SCC mix design should consider the type of manufactured sand to optimize reinforcement bonding characteristics.

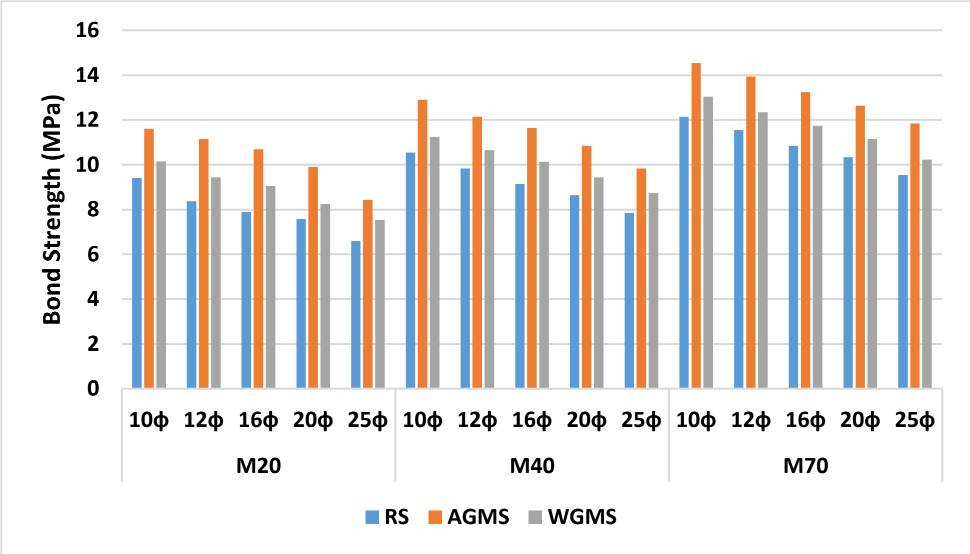

Fig. 21. Bond strength of M20, M40 and M70 grade SCC with RS, AGMS and WGMS

4. Cost Comparison Discussion: AGMS vs WGMS vs RS in Bangalore

In the context of Bangalore's construction material market, the cost of fine aggregates such as River Sand (RS), Air-Graded M-Sand (AGMS), and Wet-Graded M-Sand (WGMS) varies significantly due to availability, processing methods, environmental regulations, and logistics. River Sand (RS) is scarce and highly regulated due to environmental restrictions on river sand mining. It has a high cost due to limited legal supply and increasing transport distance. It often involves additional silt cleaning and quality uncertainty. River sand is not sustainable in the long run due to ecological impacts and mining bans.

Air-Graded M-Sand (AGMS) is produced using air separators to remove fines and control grading. It is relatively cost-effective compared to RS, offers better gradation control and uniformity. It has lower water content due to air grading making it more suitable for batching. Capital and operational cost of air classification is higher than wet processing, but material savings and performance benefits (as seen in durability tests) often justify the cost.

Wet-Graded M-Sand (WGMS) is produced and graded via wet classifiers or hydrocyclones. WGMS is typically the most economical option in terms of cost. It is easily available and has a simpler production process. WGMS may contain higher surface moisture, which can affect mix water demand.

Table 8. Cost Comparison of RS, AGMS and WGMS in Bangalore Region

Material Type	Cost (₹/ft^3)	Cost (₹/ton)	Availability	Quality Control	Sustainability	Durability (Based on Study)
RS	90–120	3200–4200	Low (regulated)	Inconsistent	Low	Moderate
AGMS	60–80	2100–2800	Moderate	High	High	High
WGMS	55–75	1900–2600	High	Moderate	Medium	Moderate

5. Conclusions

- The inclusion of AGMS in SCC shows considerable improvement in the flow properties across all grades of concrete compared to WGMS and RS.
- The evaluation of mechanical properties across M20, M40, and M70 grade self-compacting concrete (SCC) incorporating various proportions of AGMS, and WGMS in replacement of

river sand clearly established that the type and proportion of fine aggregate have a direct impact on the compressive and tensile strength of SCC.

- For compressive strength, the incorporation of air-graded M-sand led to a marked improvement, particularly at 75–100% replacement levels, across all concrete grades. This is likely attributed to the angular particle shape and optimized gradation of air-graded M-sand, which enhances the particle packing density and interlocking. Peak compressive strengths were observed in M40 and M70 grades at full replacement, outperforming river sand mixtures significantly. In contrast, wet-graded M-sand demonstrated a moderate strength gain up to 75% replacement, but showed marginal or plateaued improvements beyond that level, possibly due to its higher water absorption and finer particles that affect effective water–cement ratio and paste quality.
- In terms of tensile strength, both manufactured sand types contributed to strength enhancement, with AGMS again providing superior results, especially at intermediate replacement levels. The enhanced bond between the paste and the rough, angular M-sand particles is believed to contribute to this improvement. WGMS also improved tensile strength but showed slightly lesser performance compared to its air-graded counterpart.
- Taken altogether, the data show that AGMS is an extremely effectual substitution for river sand in SCC to improve the mechanical performance, while the best results are obtained at about 75 to 100 percent replacement. Although WGMS may prove viable, it may require adjustments to mix design in order to compensate for its influence on water demand and workability in full. The mechanical tests show a consistent performance improvement, which as a whole consolidates the ability that fabricated sands have to promote sustainable, durable concrete systems.
- Performance of Self-Compacting Concrete of across all grades with River Sand, AGMS and WGMS varies significantly in terms of different parameters and hence the durability assessment. The durability characteristics of concrete mixes with manufactured sand, in particular AGMS, are found to systematically be much superior to concrete mixes with river sand.
- Results indicate that for AGMS mixes, water absorption and porosity values are lowest of all mixes across all grades, indicating a denser and less permeable microstructure. Second, regardless of sand type, M20 mixed showed the highest water absorption and porosity, M70 showed improved resistance of pore refinement due to higher grade of concrete.
- The experimental results show that inclusion of AGMS and WGMS as fine aggregate replacements in SCC significantly reduces water permeability across all concrete grades, with AGMS showing the most pronounced improvement, particularly at higher replacement levels, thereby enhancing the durability and sustainability of the concrete mix.
- In terms of acid resistance, AGMS mixes experienced the least loss in both strength and weight under sulfuric acid exposure at 2% and 5% dilution levels. RS mixes displayed the greatest deterioration, particularly in M20 grade, indicating that river sand-based SCC is more vulnerable to aggressive environments. The performance of WGMS mixes was intermediate but consistently closer to AGMS than RS.
- The cumulative percentage loss in both weight and strength further confirmed the enhanced resistance of AGMS-based SCC to chemical attack. As concrete grade increased, all mixes showed improved durability; however, the benefit was most pronounced in AGMS, highlighting its potential in high-performance applications.
- Overall, Air Graded M-Sand proved to be the most effective fine aggregate for improving the durability of SCC. Its use can be strongly recommended as a sustainable alternative to natural river sand, especially in environments prone to chemical exposure or requiring long-term structural integrity.
- Water absorption together with porosity in SCC shows a strong correlation with RCPT values. The permeability levels of WGMS exceed those of AGMS particularly in cement-based materials at lower than grade 40. Durability of low- to medium-strength concrete depends on selecting appropriate sand types during production.
- The study confirms that porosity and water absorption can serve as reliable predictors for chloride ion permeability (RCPT) in SCC across all strength grades. The quadratic fit not only

offers accurate correlation but also reflects the nonlinear nature of transport mechanisms in cementitious systems. This relationship becomes increasingly important for high-performance concretes, where marginal improvements in microstructure yield substantial gains in durability.

- In the bond strength study, AGMS proves to be the most effective fine aggregate for enhancing bond strength in SCC, followed by WGMS and RS. The results emphasize the influence of sand type, concrete grade, and bar diameter on bond performance, guiding the selection of materials for optimized structural behavior.
- While river sand is the most expensive and least sustainable option, AGMS, despite a slightly higher production cost than WGMS, offers superior durability and quality control, making it ideal for high-performance concrete applications. WGMS, being more economical, remains a cost-effective alternative for general construction. Therefore, selection should balance performance requirements, cost constraints, and sustainability goals.

6. Implications for Practice

This study suggests that M-Sand, particularly AGMS, is an excellent alternative to natural river sand in the production of SCC, offering improved mechanical properties and durability. The findings also suggest the optimal replacement levels for mix design across various concrete grades, promoting more sustainable construction practices. Additionally, the reduced dependency on RS carries significant ecological benefits, including preservation of river ecosystems and mitigation of illegal sand mining.

The use of different types of sand in practical application should also consider economic feasibility. Due to the limited availability of RS in most parts of the country, the prices are almost two times higher than that of M-sand in the market. While AGMS demonstrated superior performance, its processing cost is typically higher than that of WGMS. Therefore, project-specific cost-benefit analyses are essential to determine the most suitable option, balancing performance gains against financial constraints.

References

[1] Martins MA, Barros RM, da Silva LRR, dos Santos VC, Lintz RC, Gachet LA, et al. Durability indicators of high-strength self-compacting concrete with marble and granite wastes and waste foundry exhaust sand using electrochemical tests. Constr Build Mater. 2021;317:125907. https://doi.org/10.1016/j.conbuildmat.2021.125907

[2] Irico S, Qvaeschning D, Mutke S, Deuse T, Gastaldi D, Canonico F. Durability of high performance self-compacting concrete with granulometrically optimized slag cement. Constr Build Mater. 2021;298:123836. https://doi.org/10.1016/j.conbuildmat.2021.123836

[3] Tufail RF, Naeem MH, Ahmad J, Waheed H, Majdi A, Farooq D, et al. Evaluation of the fresh and mechanical properties of nano-engineered self compacting concrete containing graphite nano/micro platelets. Case Stud Constr Mater. 2022;17:e01165. https://doi.org/10.1016/j.cscm.2022.e01165

[4] Suriya D, Chandar S, Ravichandran PT. Impact of M-Sand on Rheological, Mechanical, and Microstructural Properties of Self-Compacting Concrete. Buildings. 2023;13:1126. https://doi.org/10.3390/buildings13051126

[5] Tripathi D, Kumar R, Mehta P. Development of an environmental-friendly durable self-compacting concrete. Environ Sci Pollut Res. 2022;29:1-14. https://doi.org/10.1007/s11356-022-19638-5

[6] Tripathi D, Kumar R, Mehta P, Rawat V. An experimental study on the properties of SCC with manufactured sand. J Indian Chem Soc. 2020;97(10a):1673-7.

[7] Gonçalves JP, Tavares LM, Toledo Filho RD, Fairbairn EMR, Cunha ER. Comparison of natural and manufactured fine aggregates in cement mortars. Cem Concr Res. 2007;37:924-32. https://doi.org/10.1016/j.cemconres.2007.03.009

[8] Aasly KA, Danielsen SW, Wigum BJ, Norman SH, Cepuritis R, Onnela T. Review report on dry and wet grading of filler materials for concrete (COIN Project Report 52). SINTEF Building and Infrastructure; 2014. ISBN: 978-82-536-1412-0.

[9] Peng S, Wu Y, Tao J, Chen J. Airflow velocity designing for air classifier of manufactured sand based on CPFD method. Minerals. 2022;12:90. https://doi.org/10.3390/min12010090

[10] Mahalakshmi SHV, Khed VCK. Experimental study on M-sand in self-compacting concrete with and without silica fume. Mater Today Proc. 2020;27(2):1061-5. https://doi.org/10.1016/j.matpr.2020.01.432
[11] Mahakavi P, Chithra R. Effect of recycled coarse aggregate and manufactured sand in self-compacting concrete. Aust J Struct Eng. 2019;21(1):33-43. https://doi.org/10.1080/13287982.2019.1636519
[12] Janagan SS, Namachivayam N, Kabilan R, Prasath RN, Naveenkumar M. An experimental study on self compacting concrete by replacing the fine aggregate with M Sand. Int J Curr Eng Sci Res. 2019;6(3).
[13] Kumar KP, Radhakrishna. Characteristics of SCC with fly ash and manufactured sand. IOP Conf Ser Mater Sci Eng. 2016;149:012111. https://doi.org/10.1088/1757-899X/149/1/012111
[14] Baskar S, Nelson D. Experimental investigation of self-compacting concrete using M-Sand. J Chem Pharm Sci. 2015;8:947-51.
[15] Zeghichi L, Benghazi Z, Baali L. Comparative study of self-compacting concrete with manufactured and dune sand. J Civ Eng Archit. 2012;6:1429-34. https://doi.org/10.17265/1934-7359/2012.10.022
[16] Nanthagopalan P, Santhanam M. Fresh and hardened properties of self-compacting concrete produced with manufactured sand. Cem Concr Compos. 2011;33(3):353-8. https://doi.org/10.1016/j.cemconcomp.2010.11.005
[17] Dehwah HAF. Corrosion resistance of self-compacting concrete incorporating quarry dust powder, silica fume and fly ash. Constr Build Mater. 2012;37:277-82. https://doi.org/10.1016/j.conbuildmat.2012.07.078
[18] Kalirajan S, Vishnuram BG. Development of self compacting concrete using manufactured sand. Int J Earth Sci Eng. 2014;7:987-92.
[19] Mane K, Joshi A, Kulkarni D, Prakash K. Study of shrinkage characteristics of concrete made with pozzolanic materials and partly replacing river sand by MS. J Build Pathol Rehabil. 2021;6. https://doi.org/10.1007/s41024-021-00113-6
[20] Prasanth S, Chandar SP, Gunasekaran K. Flexural behaviour of self-compacting coconut shell reinforced concrete beam using manufactured sand. Innov Infrastruct Solut. 2024;9:459. https://doi.org/10.1007/s41062-024-01775-0
[21] Li H, Huang F, Tu H, et al. Pumpability of manufactured sand self-compacting concrete. J Wuhan Univ Technol Mater Sci Ed. 2023;38:1382-90. https://doi.org/10.1007/s11595-023-2832-z
[22] Bureau of Indian Standards. IS 12269:2013 - Ordinary Portland cement, 53 grade - Specification. New Delhi: BIS; 2013.
[23] Bureau of Indian Standards. IS 383:2016 - Coarse and fine aggregate for concrete - Specification (Third Revision). New Delhi: BIS; 2016.
[24] Bureau of Indian Standards. IS 10262:2019 - Concrete mix proportioning - Guidelines (Second Revision). New Delhi: BIS; 2019.
[25] Bureau of Indian Standards. IS 456:2000 - Plain and reinforced concrete - Code of practice (Fourth Revision). New Delhi: BIS; 2000.
[26] EFNARC. Specification and guidelines for self-compacting concrete. European Federation for Specialist Construction Chemicals and Concrete Systems; 2006.
[27] Bureau of Indian Standards. IS 1199 (Part 6):2018 - Fresh concrete - Methods of sampling, testing and analysis. Part 6: Tests on fresh self-compacting concrete (First Revision). New Delhi: BIS; 2018.
[28] Bureau of Indian Standards. IS 516 (Part 1/Sec 1):2021 - Compressive, flexural and split tensile strength. New Delhi: BIS; 2021.
[29] ASTM International. ASTM C642 - Standard test method for unit weight, porosity, and density of compressed building stone. West Conshohocken (PA): ASTM; 2021.
[30] ASTM International. ASTM C1202 - Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. West Conshohocken (PA): ASTM; 2019.
[31] Deutsches Institut für Normung. DIN 1048-5:1991 - Testing of concrete - Part 5: Testing of hardened concrete (specimens prepared on site). Berlin: DIN; 1991.
[32] ASTM International. ASTM C1898 - Chemical resistance of concrete products to acid attack. West Conshohocken (PA): ASTM; 2000.
[33] Bureau of Indian Standards. IS 2770 (Part 1):1967 - Methods of testing bond in reinforced concrete: Part 1 - Pull-out test. New Delhi: BIS; 1967.