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Study on Self-Compacting Concrete using Industrial Waste Material

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ABSTRACT: Self-compacting concrete (SCC) is a specialized type of concrete that can flow and settle into place without the need for external vibration, offering ease of use and efficiency in construction. However, one significant drawback of SCC is its high cost, primarily due to the additional use of chemical admixtures and Portland cement. This expense can be reduced by partially replacing cement with alternative materials such as fly ash and wood ash. Fly ash is a mineral admixture known for its compatibility with concrete, while wood ash, which contains lower levels of calcium oxide and a substantial amount of silicon dioxide, can also serve as a viable cement replacement. The incorporation of these materials not only reduces the reliance on viscosity-modifying agents but also enhances the mechanical integrity and durability of the concrete by lowering the water content. Experimental tests, including split tensile strength, compressive strength, and flexural strength, were conducted on SCC mixes containing these cement replacement materials to assess their mechanical properties. Workability tests such as slump, L-box, and V-funnel were also performed to evaluate the characteristics of the mixtures. In this study, 10% and 20% of traditional Portland cement were replaced by these alternative materials by weight, and the performance of the resulting mixtures was analyzed. To improve the workability, 1.5% of the superplasticizer Glenium B233 by weight of the cement was used as a chemical admixture. The mix was designed following the guidelines provided by EFNARC. The results of this study indicate that the optimal mix, with 10% replacement of both wood ash and fly ash, significantly increases the compressive strength of the SCC mix.

KEYWORDS: Replacement of cement, EFNARC is pursued.

I. INTRODUCTION

Concrete is one of the most widely used materials globally, second only to water (Mehta and Monteiro 2014). Its essential role in modern infrastructure, including roads, buildings, and other structures, is largely due to its cost-effectiveness in both construction and maintenance. Over time, advancements in concrete technology have been driven by the need for faster construction and improved durability. Initially, high early-strength cements allowed for easier handling by increasing water content, but this led to durability issues, particularly in harsh environments. A significant innovation in the past three decades has been the introduction of superplasticizers, which reduce water usage while maintaining workability. Additionally, the use of supplementary cementitious materials (SCMs) like fly ash, GGBS, and silica fume is becoming increasingly important in producing High-Performance Concrete (HPC).

Self-Compacting Concrete (SCC) represents a recent innovation in concrete technology, capable of flowing and compacting under its own weight without the need for vibration. This property makes SCC ideal for use in densely reinforced structures. The successful formulation of SCC requires a thorough understanding of its components and their impact on both fresh and hardened concrete properties. SCC must exhibit high fluidity, segregation resistance, and passing ability to ensure it can flow through and around reinforcement without issues.

The development of SCC began in Japan in the 1980s, driven by concerns over the durability of concrete structures and a shortage of skilled workers. The first prototype of SCC was created in 1988 using existing materials, and it performed

well in terms of drying shrinkage, heat of hydration, and overall density. Initially termed "High-Performance Concrete," it was later renamed "Self-Compacting High-Performance Concrete" to reflect its unique properties.

SCC differs from conventional concrete in that its fresh properties are critical for ensuring proper placement. Workability, fluidity, and segregation resistance must be carefully controlled. The level of fluidity is primarily managed through superplasticizers, though overdosing can lead to segregation and blockages. Segregation resistance is enhanced by incorporating fine materials or using Viscosity Modifying Admixtures (VMAs). The "open time," or the period during which SCC retains its desired properties, is also crucial and can be adjusted through the use of specific admixtures.

The advantages of SCC include improved concrete quality, faster construction times, lower overall costs, reduced environmental noise, better surface finishes, and greater design flexibility. However, it also has disadvantages, such as higher material costs, increased formwork expenses, and the need for greater technical expertise and quality control.

SCC has been applied successfully in various projects, particularly in Japan, where it was first used in a building in 1990. It has since been employed in major infrastructure projects, including bridges and large LNG tanks, as well as in underwater construction.

The objective of this study is to cast different mixes with increasing percentages of Portland Slag Cement replaced by metakaolin, determining the optimal dosage. A comparative study of M50 grade controlled SCC and SCC with the optimal metakaolin replacement at a constant W/C ratio of 0.27 and 1% superplasticizer dosage will be conducted. The hardened properties, including compressive strength, split tensile strength, and flexural strength, will be examined after 28 days, and durability performance will be assessed by subjecting concrete cubes to a temperature increase of 100°C for 24 hours..

II. METHODOLOGY

A comprehensive review of various studies investigating the incorporation of metakaolin in Self-Compacting Concrete (SCC), a specialized type of concrete designed to flow and compact under its own weight without the need for mechanical vibration. The application of metakaolin, a highly reactive pozzolan, in SCC has gained considerable attention due to its potential to enhance the mechanical and durability properties of the concrete.

Strength Enhancements: Anjali et al. (2015) conducted extensive experiments on metakaolin-enhanced SCC and demonstrated that its inclusion results in significantly higher compressive and tensile strengths compared to traditional concrete. This finding suggests that metakaolin not only contributes to the early strength gain but also enhances the long-term performance of SCC. Patil et al. (2015) further explored the effects of metakaolin on high-strength concrete, finding that an optimal replacement level of 10% of cement with metakaolin yields the highest strength. Their research highlights the importance of mix optimization to achieve superior mechanical properties.

Innovative Mix Designs: Dinakar and Manu (2014) introduced a novel mix design methodology specifically for metakaolin-enhanced SCC. Their method allowed for the production of SCC with compressive strengths of up to 120 MPa, which is significantly higher than typical values. This approach underscores the potential of tailored mix designs to maximize the benefits of metakaolin in high-performance concrete applications.

Durability Improvements: Several other studies have corroborated the positive impact of metakaolin on the durability of SCC. For instance, Mahure et al. (2014) and Nova John (2013) found that metakaolin not only improves the strength of SCC but also enhances its resistance to environmental degradation, such as chemical attacks and chloride penetration. This makes metakaolin a valuable additive in structures exposed to aggressive environments.

Optimal Replacement Levels: Research by Dinakar et al. (2013) and Patil & Kumbhar (2012) further supports the efficacy of a 10% metakaolin replacement for cement, which consistently yields the best results in terms of compressive strength and resistance to chemical attacks. Their findings indicate that this replacement level strikes a balance between enhancing mechanical properties and maintaining adequate workability.

Durability Benefits: Beulah and Prahallada (2012) along with Si-Ahmed et al. (2012) delved into the durability aspects of SCC containing metakaolin. Their studies revealed that metakaolin significantly improves the concrete's resistance to acid attacks and chloride penetration, which are critical factors for the longevity of structures. These durability benefits make metakaolin an attractive option for infrastructure projects requiring enhanced service life.

Workability Considerations: Despite the numerous advantages, Srivastava et al. (2012) noted that while metakaolin significantly enhances the mechanical properties of SCC, it can slightly compromise workability. This trade-off suggests that careful attention must be paid to the mix design and admixture selection to ensure that the SCC remains easy to place and compact without compromising its self-compacting characteristics.

Mix Design Challenges: Aggarwal et al. (2008) and Okamura and Ouchi (2003) addressed the broader challenges in SCC mix design, particularly the need to balance passing ability, filling ability, and segregation resistance. Their work emphasizes the importance of rigorous testing to ensure that SCC meets all necessary performance criteria, especially when incorporating additives like metakaolin.

Historical Context: Earlier research by Subramanian and Chattopadhyay (2002) explored mix proportioning for SCC, laying the groundwork for self-compatibility across various water-to-powder ratios. Their findings have been instrumental in guiding subsequent studies on optimizing SCC formulations, including those incorporating metakaolin.

Comparative Studies: Ding and Li (2002) provided a comparative analysis of metakaolin and silica fume, another widely used pozzolan, in concrete. Their research found that both materials effectively reduce shrinkage and chloride diffusion, thereby enhancing the durability of concrete. However, metakaolin offers additional benefits in terms of improving early strength development, making it a preferred choice in certain applications.

Simplified Mix Design Methods: Lastly, Nan Su et al. (2001) proposed an innovative mix design method for SCC that simplifies the implementation process while maintaining high-quality results. This method has been widely adopted in practice and serves as a foundation for further optimization of SCC mixes, particularly those incorporating metakaolin.

III. MIX DESIGN

Mix Design for M50 Grade with 0% replacement of cement: Step 1: Fixing the Total Cementitious or Powder Content for SCC Let the TCM = 550 kg/m³. Step 2: Calculation of Water Content in SCC 33 From the trials conducted using different water-cement ratio, keeping all other variables (percentage replacement of metakaolin, SP dosage), wn/cn ratio of 0.27% is found to be optimum based on satisfactory results of fresh property tests on SCC and also from compression strength test results. $wn/cn = ws / (cs) \quad 0.27 = ws / 550$ Therefore, $ws = 148.5 \text{ kg/m}^3$. Step 3: Determination of Coarse and Fine Aggregate Contents Total volume = 1000 litres. Assuming air content = 2%, Air = 20 litres. Net concrete volume = 980 litres. From the above, Cement content (cs) = 550 kg/m³ Water content (ws) = 148.5 kg/m³ Volume of cement (VC) = Cs/Gc litres, where Gc is the specific gravity of cement. $VC = 550/2.627 = 209.36 \text{ litres}$ Volume of water (Vw) = ws/Gw litres, where Gw is the specific gravity of water. $Vw = 148.5 / 1 = 148.5 \text{ litres}$ Volume of paste (Vpaste) = (cs/Gc + ws/Gw) litres. $Vpaste = 209.36 + 148.5 = 357.8 \text{ litres}$ 34 Volume of Total Aggregate (Vagg) = (980 - Vpaste) litres. $Vagg = 980 - 357.8 = 622.2 \text{ litres}$ In the combined grading of aggregates for SCC it was observed that the percentage of fine aggregate in the total aggregate content is 48% and the coarse aggregate is 52%. The EFNAARC guidelines for the percentage of fine aggregate should be in the range of 48% to 55% for fine aggregate in SCC is also satisfied. Volume of fine aggregate (Vfa) = 0.48 × 622.2 = 298.6 litres Volume of coarse aggregate (Vca) = 0.52 × 622.2 = 323.54 litres Fine aggregate content (F.A) = Vfa × Gfa, where, Gfa is specific gravity of fine aggregate. $F.A = 298.6 \times 2.625 = 783.8 \text{ kg/m}^3$ Coarse aggregate content (C.A) = Vca × Gca, where, Gca is specific gravity of coarse aggregate. $C.A = 323.54 \times 2.7 = 873.56 \text{ kg/m}^3$ Step 4: Calculation of Super Plasticizer (SP) Dosage After many trials, the dosage of admixture which satisfies initial slump-flow values greater than 650mm, which is necessary for the production of a flowable SCC as per EFNARC guidelines, is finalised. Dosage of SP (Auramix400) used (WSP) = 1% of total powder content. $WSP = 0.01 \times (550) = 5.5 \text{ kg/m}^3$ Table 4.1 Details of the mix proportions 35

Constituent	Cement	Water	Fine aggregate	Coarse aggregate
SP In kg/m ³	550	148.5	5.5	Ratio 1 0.27 1.425 1.588 0.01 4.2

4.2 Mix Design for M50 Grade with 15% replacement of cement: Step 1: Fixing the Total Cementitious or Powder Content for SCC Let the TCM = 550 kg/m³. Step 2: Fixing the Percentage of Metakaolin and Calculation of the Efficiency of Metakaolin After many trials, it is found that 8 % replacement of cement by metakaolin is optimum on the basis of strength studies. The efficiency of metakaolin at 28 days (k₂₈) for replacement of 15% is calculated as follows: $k_{28} = 0.005813p^2 - 0.319017p + 7.01479$ $k_{28} =$

0.00581(15)2 - 0.319017(15) + 7.01479 k28 = 3.53746 Therefore, the metakaolin percentage is 15%. Cement content (cs) = 467.5 kg/m³ Metakaolin content (m) = 82.5 kg/m³ 36 Step 3: Calculation of Water Content in SCC From the trials conducted using different water-cement ratio, keeping all other variables (percentage replacement of metakaolin, SP dosage), wn/cn ratio of 0.27% is found to be optimum based on satisfactory results of fresh property tests on SCC and also from compression strength test results. $wn/cn = ws / (cs+k28 \times m)$ $0.27 = ws / (467.5 + (82.5 \times 3.53746))$ Therefore, $ws = 205.022$ kg/m³. Step 4: Determination of Coarse and Fine Aggregate Contents Total volume= 1000 litres. Assuming air content= 2%, Air =20 litres. Net concrete volume= 980 litres. From the above, Cement content (cs) = 467.5 kg/m³ Metakaolin content (m) = 82.5 kg/m³ Water content (ws) = 205.022 kg/m³ Volume of cement (Vc) = cs/Gc litres, where Gc is the specific gravity of cement. $Vc = 467.5/2.627 = 177.96$ litres Volume of metakaolin (Vmetakaolin) = m/Gm litres, where Gm is the specific gravity of metakaolin. $Vm = 82.5/2.5 = 33$ litres 37 Volume of water (Vw) = ws/Gw litres, where Gw is the specific gravity of water. $Vw = 205.022 / 1 = 205.022$ litres Volume of paste (Vpaste) = (cs/Gc + m/Gm + ws/Gw) litres. $Vpaste = 177.96 + 33 + 205.022 = 416.18$ litres Volume of Total Aggregate (Vagg) = (980–Vpaste) litres. $Vagg = 980 - 416.18 = 563.82$ litres In the combined grading of aggregates for SCC it was observed that the percentage of fine aggregate in the total aggregate content is 48% and the coarse aggregate is 52%. The EFNAARC guidelines for the percentage of fine aggregate should be in the range of 48% to 55% for fine aggregate in SCC is also satisfied. 38 Volume of fine aggregate (Vfa) = 0.48 $\times 563.82 = 270.634$ litres Volume of coarse aggregate (Vca) = 0.52 $\times 563.82 = 293.19$ litres Fine aggregate content (F.A) = Vfa $\times Gfa$, where Gfa is specific gravity of fine aggregate. $F.A = 270.634 \times 2.625 = 710.414$ kg/m³ Coarse aggregate content (C.A) = Vca $\times Gca$, where Gca is specific gravity of coarse aggregate. $C.A = 293.19 \times 2.7 = 791.613$ kg/m³ Step 5: Calculation of SuperPlasticizer (SP) Dosage After many trials, the dosage of admixture which satisfies initial slump-flow values greater than 650mm, which is necessary for the production of a flowable SCC as per EFNARC guidelines, is finalised. Dosage of SP (Auramix400) used (WSP) = 1% of total powder content. $WSP = 0.01 \times (467.5 + 82.5) = 5.5$ kg/m³. Table 4.2 Details of the mix proportions Constituent In kg/m³ Cement 467.5 Water 205.022 Fine Aggregate Coarse aggregate Metakaolin 82.5 SP 5.5 710.414 791.613 Ratio 1 0.438 1.519 1.693 0.176 0.011

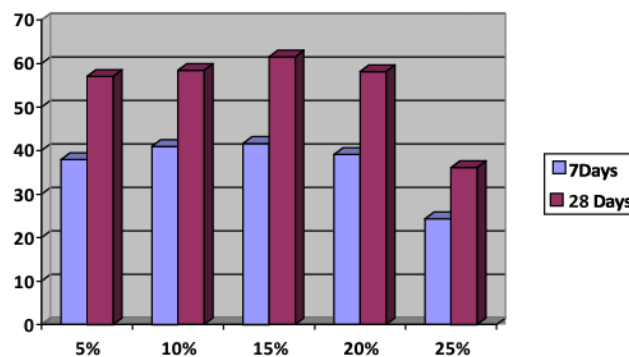
IV. CONCLUSION AND FUTURE SCOPE

This chapter includes the test results on both fresh and hardened properties of concrete. The results of compressive strength for different water/cement ratio and different percentage replacements of Metakaolin each for 7 and 28 days are given in the table below:

S. no	W/C	% Replacement of cement by Metakaolin	% SP	7 Days compressive Strength (MPa)	28 Days Compressive Strength (MPa)
1	0.33	5	1	37.91	57.053
2	0.38	10	1	40.97	58.45
3	0.43	15	1	41.67	61.53
4	0.48	20	1	39.1	58.15
5	0.53	25	1	24.35	36.16

Initially for two trail mix compressive strength for 28 days samples were determined by using Accelerated Curing Test method (ACT). The test results obtained were not accurate as the result of compressive strength at 7 days are more than 28 days strength. This may be probably due to in- compatibility of chemical admixture when subjected to higher temperature.

In the present study the grade of concrete was fixed to M50. In trail mix 4 and 9 strength criteria was in accordance with M50 grade concrete but, for the trail mix 4 the fresh concrete properties are not satisfied. Therefore from the above values for compressive strength we can conclude that the optimum replacement percentage is 15 at a W/c ratio of 0.43.



Compressive strength for different percentage replacement of Portland Slag Cement with Metakaolin

From the above graph it can be inferred that the optimum percentage replacement of Portland Slag Cement with Metakaolin is found to be 15%.

Material Quantities per Cubic Meter of Concrete

Material	Quantity (kg/m ³)	
	0% replacement	15 % replacement
Cement	550	467.5
Metakaolin	0	82.5
Water	148.5	205.022
Fine aggregate	783.89	710.663
Coarse aggregate	873.478	791.851
Superplasticizer and VMA	5.5	5.5

Both mixes are designed at a constant water to cement ratio (W/C) of 0.27 and at 1% superplasticizer dosage.

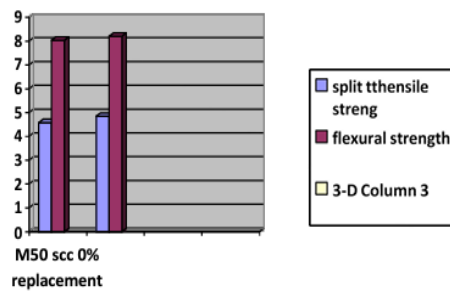
Fresh concrete properties

% Replace ment of cement With Metakao lin	Flow time (sec)	Slump flow (mm)	L-Box	U-Box (mm)
0	2.06	780	0.98	1
5	2.21	765	0.94	5
10	2.36	745	0.89	9
15	3.08	720	0.873	15
20	3.9	690	0.832	21
25	5.01	646	0.813	27

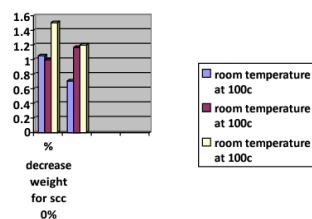
Split tensile and flexural strength values

Hardened properties @ 28 days	M50 SCC (0% replacement)	M50 SCC (15% replacement)
Split tensile strength (MPa)	4.576	4.844
Flexural strength (MPa)	8.04173	8.2093

Compressive strength of SCC cube subjected 100C raise in temperature



Weight of SCC cube subjected 100 raise in temperature



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