Study on the effect of sintered flyash aggregate and steel fibre on the properties of high performance concrete

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Abstract. Light weight aggregates are better solutions for making the structure light weight and they are widely used in construction. Other than the light weight behaviour, the porous nature of these aggregates helps in retaining water content and aids in curing the concrete. Sintered flyash aggregate (SINTAG) is a type of light weight aggregate that can be used as coarse aggregate in concrete. Water content retained through presoaking these aggregates helps in extended hydration of cementitious materials and can increase the strength of concrete even in the absence of proper external curing practice. Steel fibre reinforcement can increase the tensile and flexural strength of concrete. Presoaked SINTAG was added by replacing various percentages of coarse aggregate volume in concrete and steel fibre was added at different percentages by volume of concrete. It was obtained that 20% replacement of coarse aggregate by volume with SINTAG increased the strength of normal concrete by 26.7% and split tensile strength increased by 2.8%. Addition of steel fibres to SINTAG concrete at 1% increased its compressive strength additionally by 6.2% and tensile strength additionally by 35.1%. Durability studies showed that chloride ion penetration of normal and SINTAG incorporated concrete were low. Water permeability tests revealed that normal, SINTAG and fibre reinforced SINTAG concretes can be used for water retaining structures as well as aggressive environments. Flexural strength of normal RCC beam increased 7.7% when SINTAG was incorporated while it again increased 9.6% when steel fibre was added. Fibre reinforced SINTAG concrete beam showed much less deflection compared to normal and SINTAG beams.

1. Introduction
Curing is essential to prevent the moisture loss and shrinkage cracks at the early ages of concrete. Other than the initial strength characteristics, the long term performance of concrete is mainly achieved through a good curing practice. An effective curing practice enhances the hydration process of cementitious materials which fills the pore spaces improving the durability and strength properties of concrete.

For concrete containing pozzolanic materials and a low water to cementitious material ratio (w/cm), the mixing water is inadequate to hydrate all cementitious materials. Effective hydration on the surface
of concrete by readily available external moisture makes it to become impermeable and leaving unhydrated cementitious grains in the inside. In high performance concrete, external curing becomes ineffective due to its low permeability properties because of the disconnected capillary pore system [1]. The hydration of these unhydrated grains can constitute a higher strength of concrete. Internal curing is an effective solution for such type of concrete and can be achieved through the distribution of adequate moisture content inside the concrete which aids in hydration. In this method extra water content other than the mixing water is retained inside the concrete using certain curing agents or light weight aggregates. The ready supply of moisture inside the concrete helps in maximum hydration of cementitious materials and avoids self-desiccation which can improve the properties of concrete.

Light Weight Aggregates (LWAs) consist of interconnected porous structure and can be effectively used for internally curing the concrete. These LWAs are presoaked to ensure desired degree of water absorption and added to the concrete. The water retained in the relatively larger pores of LWAs is naturally drawn into the smaller pores of the cement paste and enhances the hydration process [2]. The water present in the pores of prewetted LWAs is absorbed by the unhydrated cement particles in HPC for its complete hydration as well as the internal humidity of concrete is retained for a much longer period [3]. The movement of water from the inside of saturated LWAs to the surrounding cement paste depends on their relative humidity [4]. The increased surface area of saturated LWAs helps in uniform distribution of water throughout the microstructure of concrete. Also the emptied air voids in LWAs protects the concrete from freezing and thawing cycles [5]. The surrounding cement paste infiltrate into the porous surface of LWAs and bond tightly. These well bonded interfacial zones of light weight aggregates also constitute high strength development [6]. A comparative study on chemical reactivity of different artificial LWAs in cement paste show that the pozzolanic activity is higher in the case of SINTAG [7].

Sintered fly ash aggregate (SINTAG) is a type of light weight aggregate that can be used as coarse aggregate in concrete. This study investigates the application of pre-soaked SINTAG as an internal curing agent in concrete. These aggregates were added to the concrete by replacing equal volume of coarse aggregate.

2. Materials

2.1 Cement
Ordinary Portland cement of 53 grade conforming to IS 12269-1987 was used in the study.

2.2 Aggregates
Manufactured sand passing through 4.75 mm IS sieve was used as fine aggregate. Coarse aggregate used for the study was the crushed stone of maximum size 20 mm with specific gravity of 2.71.

2.3 Sintag
Coarse SINTAG, nearly round pellets, (6 – 14 mm size) with density of 872 kg/m³ and specific gravity of 2.02 was used as partial replacement of coarse aggregate. These aggregates are made by heating fly ash pellets in rotary kiln at a temperature of 1200°C and the product obtained consists of a harder outer layer and spongy porous inner structure which is light weight and water absorbent.
2.4 Steel Fibre
Hooked mild steel wires of 3 cm length, 0.5 mm diameter and a tensile strength of 1172 MPa was used as steel fibres for study.

2.5 Silica Fume
Silica fume was added at the rate of 3% by weight of cement.

2.6 Superplasticizer
Sulphonated naphthalene formaldehyde condensate type superplasticizer was used to reduce water content and satisfy workability conditions.

3. Mix Proportion and Methodology
For the experimental study, the mix was designed to obtain a characteristic strength of 35 MPa having a mix proportion of 1: 1.8: 3 with water cement ratio of 0.38. All mixes followed a cement content of 400 kg/m$^3$ and silica fume at the rate of 3% by weight of cement. The super plasticizer dosage was adjusted to 1.2% by weight of cement to obtain a slump value of 80 mm. SINTAG was pre-soaked for 2 hours to ensure a minimum water absorption of 10% prior to mixing. In the first phase, sintered fly ash aggregate was added replacing 5%, 10%, 15%, 20%, 25% and 30% by volume of coarse aggregate. The improvement in compressive strength was excellent, whereas increase in tensile strength was not promising. So in the second phase, to increase the tensile and flexural properties, steel fibre was added at 0.5%, 0.75%, 1%, 1.25%, 1.5% and 2% by volume of concrete.

4. Preparation, Curing and Testing of Specimens.
Standard cube and cylinder specimens were cast as per IS 516-2004 for testing the compressive strengths, tensile strengths and modulus of elasticity respectively. Standard cube specimens were cast for testing water permeability and small cylinder specimens of 100 mm diameter and 50 mm thickness were cast to test chloride penetration. Beam specimens of size 150 mm x 200 mm x 1200 mm were cast to determine the flexural properties. The beams were reinforced with 12 mm diameter bars having yield strength of 415 N/mm$^2$ with hooked ends as longitudinal reinforcement and 8 mm stirrups at 150 mm c/c.

All the specimens were given water curing followed by air curing at ambient temperature inside laboratory till the period of testing.

The compressive strength of cube specimens corresponding to 7, 28 and 56 days, split tensile strength and modulus of elasticity corresponding to 28 days were measured as per IS 516-2004. Durability tests were conducted at 56 days. Water permeability tests were conducted as per DIN 1048 (Part 5) at 5 bar pressure. Rapid Chloride Penetration Test (RCPT) was conducted as per ASTM C 1202. RCC beams were tested using 100 ton loading frame and LVDT at 28 days under two point loading to understand the flexural strengths and deflection properties.

5. Results and Discussion

5.1 Strength Tests
5.1.1 Compressive Strength Tests
Table 1 shows the compressive strengths of concrete having different replacements of coarse aggregate with SINTAG. Table 2 shows compressive strengths of concrete having different percentages of steel fibre added to 20% SINTAG concrete.
Table 1. Compressive strength test results (Coarse aggregate replaced with fly ash aggregate)

| % Replacement | Mix designation | 7th day strength (N/mm²) | 28th day strength (N/mm²) | 56th day strength (N/mm²) |
|---------------|-----------------|--------------------------|---------------------------|--------------------------|
| 0% (Normal)   | M₀              | 36.66                    | 47.55                     | 49.77                    |
| 5% SINTAG     | M₂ S₅          | 38.32                    | 48.77                     | 54.56                    |
| 10% SINTAG    | M₂ S₁₀         | 40.24                    | 53.30                     | 59.93                    |
| 15% SINTAG    | M₂ S₁₅         | 41.72                    | 56.18                     | 62.35                    |
| 20% SINTAG    | M₂ S₂₀         | 43.35                    | 59.72                     | 65.86                    |
| 25% SINTAG    | M₂ S₂₅         | 41.86                    | 57.76                     | 63.13                    |
| 30% SINTAG    | M₂ S₃₀         | 37.44                    | 51.33                     | 59.31                    |

The result shows that compressive strength of internally cured concrete with 20% SINTAG is highest and is 26.7% higher than normal concrete at 28 days and 32.3% at 56 days. The significant increase in strength can be attributed to the formation of additional C-S-H gel due to hydration of unhydrated cement particles by water available from the pores of the lightweight aggregate. Also the C-S-H gel infiltrate into the surface pores of SINTAG thus making the otherwise weak Inter Transition Zone (ITZ) stronger.

Table 2. Compressive strength test results (Steel Fibres added to 20% SINTAG concrete)

| Steel fiber addition with 20% SINTAG | Mix designation | 7 day compressive strength, N/mm² | 28 day compressive strength, N/mm² | 56 day compressive strength, N/mm² |
|------------------------------------|-----------------|----------------------------------|-----------------------------------|-----------------------------------|
| 20% SINTAG concrete                | M₂ S₂₀          | 43.35                            | 59.72                             | 65.86                             |
| SINTAG 20% + Fiber 0.25%           | M₂ S₂₀ F₀.2₅    | 44.02                            | 60.64                             | 67.11                             |
| SINTAG 20% + Fiber 0.5%            | M₂ S₂₀ F₀.₅₀    | 44.98                            | 61.25                             | 67.98                             |
| SINTAG 20% + Fiber 0.75%           | M₂ S₂₀ F₀.₇₅    | 45.62                            | 62.46                             | 68.55                             |
| SINTAG 20% + Fiber 1.0%            | M₂ S₂₀ F₁.₀     | 46.₄₅                            | ₆₃.₄₆                             | ₆₉.₈₁                             |
| SINTAG 20% + Fiber 1.25%           | M₂ S₂₀ F₁.₂₅    | 45.₈₇                            | ₆₂.₈₃                             | ₆₈.₆₂                             |
| SINTAG 20% + Fiber 1.5%            | M₂ S₂₀ F₁.₅     | ₄₅.₂₃                            | ₆₁.₇₆                             | ₆₇.₈₈                             |

From the table it can be seen that compressive strength of 1% fibre reinforced concrete with fly ash aggregate at 28 days is highest and is 6.2% higher than fly ash aggregate concrete without fibre and is 33.5% higher compared to normal concrete. It can be understood that the contribution of steel fibre in increasing the compressive strength of concrete is very less compared to the contribution of SINTAG.
5.1.2 Split Tensile Strength Tests
Normal mix showed a split tensile strength of 4.24 MPa, 20% SINTAG concrete 4.36 MPa and 5.89 MPa when 1% fibre was also added to SINTAG concrete. Thus increase in split tensile strength was only 2.8% when SINTAG was incorporated to normal concrete. Increase in tensile strength of fibre reinforced SINTAG concrete is 35.1% compared to SINTAG concrete and is 38.9% compared to normal concrete. It can be seen that the contribution of SINTAG to increase in tensile strength is feeble whereas fibre reinforcement contributed significantly.

5.1.3 Modulus of Elasticity Tests
Normal mix obtained a modulus of elasticity of 3.31x10^4 MPa, 20% SINTAG concrete 3.62x10^4 MPa and 1% fibre reinforced SINTAG concrete 3.74x10^4 MPa. The increase in modulus of elasticity was 9.36% when SINTAG was introduced to normal concrete where as it increased again by 3.31% when 1% steel fibre was added.

5.2 Durability Tests

5.2.1 Water Permeability
Figure 1 shows the experimental setup for water permeability test as per DIN standards.

![Figure 1. Test setup for water permeability](image)

Normal concrete had a maximum depth of penetration of 25.75 mm, SINTAG concrete of 21.9 mm and Fibre reinforced SINTAG concrete of 25.85 mm. As per water permeability criteria of Concrete Society 1998, concrete having a penetration less than 30 mm can be used in aggressive environments and less than 50 mm can be used in water retaining structures. Thus all the three types of concretes can be categorised under high performance when water retention is considered. Even though SINTAG is porous, the formation of strong Inter Facial Zone on the surface of the light weight aggregate might have prevented water penetration through SINTAG [8].
5.2.2 Rapid Chloride Penetration

Figure 2 shows the experimental setup for Rapid Chloride Penetration Test (RCPT)

![Rapid Chloride Penetration Test setup](image)

**Figure 2.** Rapid Chloride Penetration Test setup

Figure 3 shows the Current Vs Time graph for RCPT for the Normal and SINTAG concretes. This test cannot be conducted for Steel Fibre Reinforced concrete as conductivity of steel fibres will damage the equipment and give erroneous results.

![Current Vs Time graph](image)

**Figure 3.** Graphical representation of Current Vs Time

From calculations it is obtained that the total charge passed is 1446.3 coulombs for normal concrete and 1476 coulombs for 20% SINTAG incorporated concrete. As per RCPT classification criteria of ASTM C 1202, both the concretes have a total charge passed between 1000 and 2000 coulombs, which come
under low chloride ion permeability category. So the concrete satisfies high performance criteria as per RCPT also.

5.3 Flexural Behaviour of RCC Beams

Figure 4 shows the experimental setup for testing the flexural behaviour of RCC beams.

![Figure 4. Test setup for Flexural behaviour of RCC beams](image)

Figure 5 shows the Load–Deflection graph for Normal concrete, SINTAG concrete and Fibre reinforced SINTAG concrete.

![Figure 5. Load-Deflection graph for RCC Beams](image)

Normal beam carried a maximum load of 140 kN, SINTAG beam 150.6 kN and Fibre reinforced SINTAG beam 165 kN. Normal beam had initial crack formation at 33 kN, SINTAG beam at 35 kN and Fibre reinforced SINTAG beam at 44 kN. Flexural strength of normal beam is 23.3 MPa, SINTAG beam is 25.1 MPa and Fibre reinforced SINTAG beam is 27.5 MPa.
The increase in flexural strength of SINTAG beam compared to normal beam can be attributed to increase in its compressive strength whereas additional increase in flexural strength of fibre reinforced SINTAG beam can be attributed to its increase in its tensile strength. It can be seen from graph that, as expected, deflection significantly reduced when fibre was added.

6. Conclusions

- The optimum percentage of fly ash aggregate obtained is 20%, and steel fiber is 1% for highest compressive strength and tensile strength.
- The compressive strength of internally cured concrete with 20% fly ash aggregate is 26.7% higher compared to normal concrete at 28 days.
- The compressive strength of concrete having SINTAG + Steel Fiber is 6.2% higher than SINTAG concrete and 33.5% higher than normal concrete at 28 days.
- The split tensile strength of SINTAG concrete is 2.8% higher and SINTAG + Fibre concrete is 38.9% higher compared to control mix at 28 days.
- Water permeability of all the three types of concrete is less than 30 mm and so it can be used in water retaining structures as well as in aggressive environment.
- The resistance of fly ash aggregate incorporated concrete to chloride penetration is almost similar compared to the normal concrete. Normal and fly ash aggregate concrete shows low chloride penetrability and can be classified under high durability category.
- The flexural strength of normal RCC beam of size is 23.3 N/mm², SINTAG beam is 25.1 N/mm² and Fiber reinforced SINTAG beam is 27.5 N/mm².
- Flexural strength increment compared to normal concrete beam is 7.7% when SINTAG was incorporated, where as it is 18 % when steel fiber was also added.
- The deflection of Fiber reinforced SINTAG beam is very low compared to other two types of beams.

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