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Experimental and Statistical Investigations on Alccofine Based Ternary Blended High-performance Concrete

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PAPER INFO	*ABSTRACT*

This paper investigates the potential benefits of Ternary blended High-performance concrete containing Silica fume (SF) and Alccofine (AL) as partial cement replacements. The experimental program contains a total of 14 mixes with a water to binder ratio of 0.4 and varying percentages (0-20%) of Silica fume and Alccofine both as binary and ternary blended. Fresh and hardened properties of concrete were evaluated based on slump, compressive strength, flexural strength, split tensile strength and water absorption tests. Ternary mixes containing SF and AL increased concrete compressive strength by 14-27% and tensile strength by 26-43% compared to the reference mix. Rise in early strength development for all the ternary blended mixes is attributed to the presence of highly reactive alccofine. Higher replacement of Alccofine more than 10% led to a steady decrease in strength due to dilution effect, whereas for silica fume, the strength dilution was gradual beyond 15% replacement. Denser particle packing reduced water absorption in ternary mixes. A mix containing 15% SF and 5% AL showed 65.7% reduction in water absorption compared to reference mix. Synergy assessment were done for all the ternary mixes, peak result was obtained for a mixture containing 10% SF and 10% AL. Based on the experimental data, empirical models were developed and compared with the existing codes and earlier researches. Empirical models proposed in this study have the least Integral Absolute Error (IAE) of 0.47% and 1.55% in predicting flexural strength and split tensile strength based on compressive strength of concrete.

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1. INTRODUCTION

In recent years, there is a steady growth in the consumption of concrete due to growing population and rapid modernization. Due to the increased demand, there is a continual depletion of natural resources that forms the key constituents of the cement industry. On the other hand, improper disposal of industrial by-products has reported landfill problems causing adverse effects on the environment [1, 2]. Some of these industrial by-products have cementitious values and are being used as partial cement replacements. Supplementary cementitious materials (SCMs) such as Fly ash (FA), Silica fume (SF), Metakaolin (MK), Alccofine (AL), Rice husk ash (RHA) and ground granulated blast-furnace slag (GGBS) are rich in silica and alumina content essential for the strength development of concrete [3, 4].

Modern concrete has to grow along with the fast-growing world and has to serve bigger purposes beyond strength criterion i.e. early strength development and durability. High-performance concrete (HPC) is predominantly being used in high-rise buildings, bridges and marine structures where erection time and durability are critical factors [5]. The mentioned conditions can be fulfilled by three methods 1) by using special types of cement, which has high production cost and are therefore not suitable for most cases 2) steam curing, where implementation might be quite tedious in actual field practices 3) using mineral admixtures. Eventhough numerous studies have reported the benefits of using SCMs in concrete, incorporating higher dosages of SCMs in binary form can often lead to negative side effects such as dilution of strength and extended setting time [6, 7]. One possible way to overcome such disadvantages is to

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use combinations of mineral admixtures subjected to demand, where the potential synergy between two different SCMs can be explored [8, 9].

The packing density of concrete can have a huge influence on strength and durability. Using mineral admixtures with varying particle sizes can result in denser matrix. In the case of ultrafine silica fume (about 100 times finer than cement), the wide size gap was filled by incorporating metakaolin (finer than cement and coarser than SF) which further improved concrete microstructure [10]. On the other hand, increasing particle packing densities reduces void gaps and brings out the excess water present in the pores for the lubrication of binder particles [11], highly essential for HPC where lower water to binder ratio is adapted.

Several researchers have pointed out the effectiveness of ternary blending (cement + two different SCMs). Ahmed et al. [12] studied chloride ion penetration in concrete mixes and observed a significant decrease in average charge passed for a mix containing ternary blend of 25% FA and 10% SF compared to corresponding binary blend. Jung et al. [13] reported that ternary blending of SCMs can be a suitable alternative to type IV cement in preventing thermal cracks caused due to high heat of hydration. Murthi et al. [14] studied the effect of nanomaterials in the early strength development of ternary blended concrete. In the case of fly ash known for its long-term mechanical and durability properties, it has shortcomings such as poor early strength development, which can be overcome by adding finer materials such as silica fume, metakaolin [15, 16].

Alccofine-1203 is an ultra-fine form of slag produced as a result of controlled granulation process. It has been well documented that this low calcium silicate-based admixture is highly reactive and eco-friendly. Even though several studies have reported the effects of using alccofine in binary form [17, 18]; Only fewer studies have been carried out with alccofine as a ternary additive in cement concrete, particularly in HPC. A replacement of 10% alccofine in fly ash-based geopolymer resulted in increased load-carrying capacity in compression [19]. Soni et al. [20] reported increased particle packing due to the addition of fly ash and alccofine, and increased early strength development powered by alccofine's high reactivity.

In view of the aforementioned knowledge about the past studies, this present study aims to investigate the effects of adding silica fume and alccofine both in binary and ternary form on the mechanical and durability aspects of HPC. Synergy assessment is done for all the ternary mixes in compression, flexural and split tensile strength. From the results obtained through experimental works, empirical relations have been formulated to predict flexural and split tensile strength based on compressive strength. Finally, a cost-based analysis is

carried out to examine the economical deviations with strength and durability of concrete.

2. RESEARCH SIGNIFICANCE

The concrete industry is now wide awake of the limiting raw materials for construction. Combinations of SCMs provide superior workability, strength and durability, which are essential for High strength concrete structures where frequent repair and rehabilitation is a major setback considering economic, environmental and exertion levels. Despite the vast numbers of research published and growing interest in ternary blended concrete, limited information has been documented on the interaction between SCMs and synergy evaluation. This study emphasizes on the performance comparison of a new blended cement in HPC containing two ultrafines SF and AL, both in binary and ternary forms. Empirical relations from the existing codes to predict tensile strength based on compression tends to deviate more in the case of combinations of SCMs, not just in the case of this study, but rather in most ternary mixes from previous researchers. Hence re-evaluation of empirical relations is necessary for SCM replaced concrete.

3. EXPERIMENTAL PROGRAM

The following methodology discussed in this section has been tailored to attain the objectives of the proposed study.

3. 1. Material Properties   Ordinary Portland cement of 53-grade with a 28-day compressive strength of 54.5 Mpa and specific gravity of 3.12 confirming to IS 12269-2013 [21], is used as cementing material for all the mixes. Silica fume is a superior ultrafine mineral admixture now available in markets everywhere and was obtained from Astrra Chemicals Pvt Ltd complying with ASTM C1240 [22]. Alccofine-1203 is an ultra-fine form of GGBS processed through controlled granulation, are highly reactive in nature. The particles have irregular shapes with sizes mostly falling under the range of 4-10 μm. The particle size distribution of OPC, SF and AL are shown in Figure 1. Chemical compositions and tested physical properties of OPC, SF and AL are mentioned in Tables 1 and 2, respectively. Manufactured sand confirming to zone II sieve passing percentage of IS: 383-1970 [23] is used as fine aggregate for all the mixes. Fine aggregate has the specific gravity of 2.67, fineness modulus of 2.72 and water absorption of 0.96% at an interval of 24 h. Crushed granite rock of size not less than 12.5 mm is used as coarse aggregate. Coarse aggregate has the specific gravity of 2.7, fineness modulus of 6.67
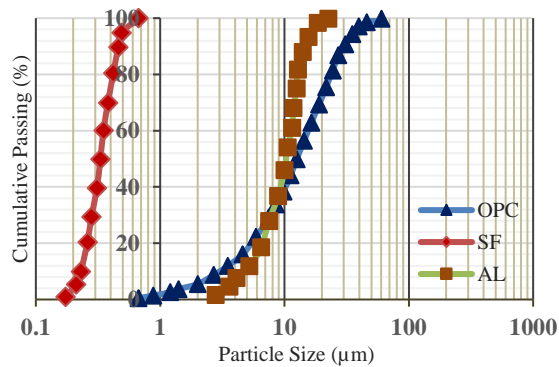
Figure 1. Particle size distribution of OPC, SF and AL

Bulk density (kg/m^3)	1550	600	820
Standard consistency (%)	27.4	-	-
Setting time (min)			
Initial	110	-	-
Final	300	-	-

and water absorption of 0.70% at an interval of 24 h. Sulfonated Naphthalene Formaldehyde based high range water reducer confirming to IS: 9103-1999 [24] and ASTM C494 [25] with a specific gravity of 1.2 ± 0.05 is used as superplasticizer.

3. 2. Mix Proportioning and Preparation of Specimens   A total of 14 mixes were proportioned using guidelines and specifications recommended by ACI 211.4R-93 [26]. Four binary mixes with both SF and AL with replacement levels of 5-20% and five ternary mixes with a maximum replacement of 15% and 20% were prepared. For all the mixes fine aggregate content is reduced corresponding to the volume change from the addition of SCMs. Superplasticizer content was varied by weight of cementitious materials in order to ensure the desired workability, with a slump not less than 75 mm. The mixture proportions used in this experimental program are summarized in Table 3. Concrete was carefully mixed in a tilting type mixer machine and placed in cubical moulds of size 100 mm x 100 mm x 100 mm, cylindrical moulds of size 100 mm x 200 mm and prism moulds of size 100 x 100 mm x 500 mm. For every mix, 3 Numbers of specimens were cast. The specimens after de-moulding were allowed for curing in a laboratory controlled environment.

TABLE 1. Chemical composition of OPC,SF and Al (%)

Chemical composition	OPC	SF	AL
SiO$_2$	21.07	92.06	21-23%
Al$_2$O$_3$	5.54	0.48	5-5.6%
CaO	64.26	0.4	61-64%
Fe$_2$O$_3$	5.16	2.11	3.84.4%
MgO	0.86	0.63	0.81.4%
K$_2$O	0.37	1.24	-
P$_2$O$_5$	0.33	0.02	-
LOI	1.54	2.54	-

TABLE 2. Physical properties of OPC, SF and AL

	OPC	SF	AL
Specific gravity	3.1	2.63	2.9
Specific surface area (cm^2/g)	-	18800	12000

TABLE 3. Mixture proportioning of Binary and Ternary blended concrete

Mix No.	Mix	C, Kg	SF, Kg	AL, Kg	W, Kg	FA, Kg	CA, Kg	SP (%)
M1	Control	450	-	-	179	669	1099	-
M2	SF-5	427.5	22.5	-	179	629	1099	0.5
M3	SF-10	405	45	-	179	589	1099	0.5
M4	SF-15	382.5	67.5	-	179	549	1099	0.5
M5	SF-20	360	90	-	179	509	1099	0.5
M6	AL-5	427.5	-	22.5	179	640.5	1099	0.75
M7	AL-10	405	-	45	179	612.1	1099	0.75
M8	AL-15	382.5	-	67.5	179	583.6	1099	0.75
M9	AL-20	360	-	90	179	555.1	1099	0.75
M10	SF-5, AL-10	382.5	22.5	45	179	572.1	1099	0.85
M11	SF-10, AL-5	382.5	45	22.5	179	560.5	1099	0.85
M12	SF-15, AL-5	360	67.5	22.5	179	520.5	1099	0.85
M13	SF-10, AL-10	360	45	45	179	532.1	1099	0.85
M14	SF-5, AL-15	360	22.5	67.5	179	543.6	1099	0.85

3. 3. Testing Methods   To determine the workability of fresh concrete, slump test was performed in accordance with ASTM C143 [27]. Compression testing machine with a maximum load-carrying capacity of 3000 kN is used to test cube samples. Split tensile strength test was conducted in a Universal testing machine to determine the indirect tensile strength of concrete as per specifications of ASTM C 496-90 [28]. Flexural strength test was performed as per the specifications of ASTM C78 [29] using a three-point loading system. Samples were taken after curing at a temperature of 27±2°C (90-95% Relative Humidity) and surface dried before testing. Sample preparation and testing are shown in Figure 2.

4. RESULTS AND DISCUSSION

The results of mechanical and durability properties obtained from the tested samples of binary and ternary blended concrete are discussed in this section.

4. 1. Workability of Concrete   Workability is a paramount fresh concrete property to measure the ease in mixing, transporting and placing concrete without much segregation, bleeding, loss of materials and energy consumption, while maintaining homogeneity. Addition of different SCM shows distinct effect on the workability of concrete. In this study, three different superplasticizer dosages were used for SF concrete, AL concrete and Ternary blended concrete to attain a slump not less than 75 mm. Addition of SF increased workability due to its fine and spherical shaped particles, whereas slump degradation was observed significantly for higher dosages of AL. Ternary mixes containing SF and AL provided better slump with a homogeneous and cohesive mixture. Slump values for all the mixes in this present study are mentioned in Figure 3.

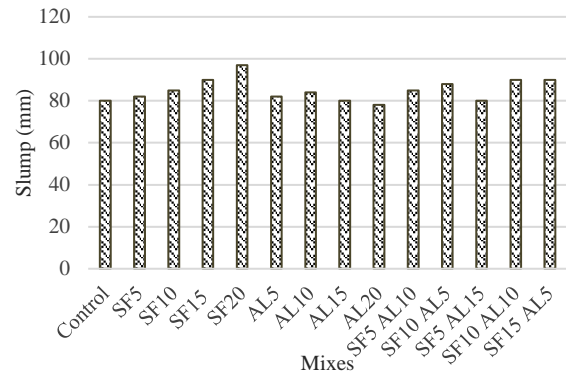**Figure 2.** Sample preparation and testing

Figure 3. Slump values of the Mixes

4. 2. Mechanical Properties of Concrete

4. 2. 1. Compressive Strength   The compressive strength results of tested cube samples are presented in Figure 4. Tests were performed on four curing ages of 7, 14, 28 and 45 days for all the mixes. Replacement of cement with SF in the control mix significantly increases the compressive strength, Figure 5(a) shows the improvement in the strength of SF replaced concrete mixes for different curing ages. The silica-rich SF reacts with portlandite to produce additional C-S-H gel which progressively densifies the matrix resulting in increased strength [30]. AL replacement with cement rapidly increased strength due to its highly reactive components, maximum value was observed for a 10% replacement. Figure 5(b) shows improvement in the strength of AL replaced HPC mixes for different curing ages. For SF binary concrete a maximum strength increment of 20.8% was attained for 15% replacement at 28-day period, after which there is a gradual decrease in the strength primarily due to dilution effect. For AL binary concrete, a maximum strength increment of 17.9% was observed for a 10% replacement, after which a significant dropdown in the strength was noticed. In the case of both SF and AL the strength increments and decrements are in
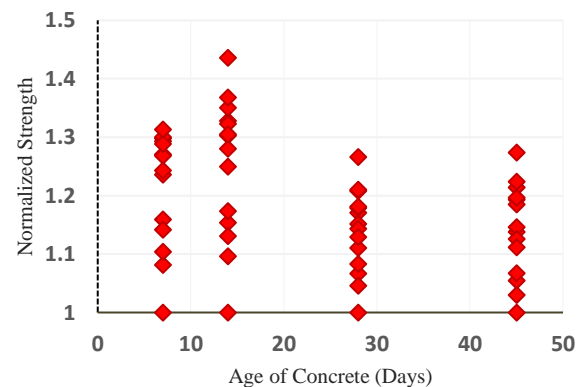

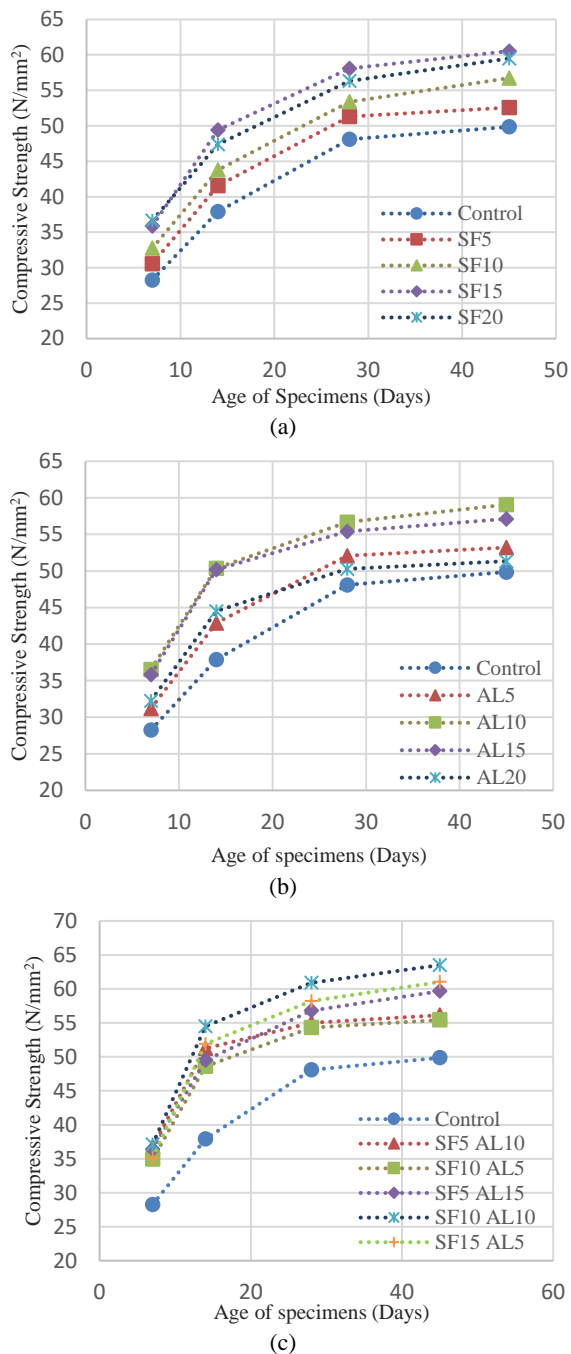**Figure 4.** Strength Improvement of concrete in compression

(a)

(b)

(c)

Figure 5. Compressive strength test results (a) SF blended concrete (b) AL blended concrete (c) Ternary blended concrete

compliance with their corresponding pozzolanicity and dilution effect. AL contains highly active silica and calcium content which results in rapid crystallization and hardening essential for early strength development, but on the negative side, a significant decrement is observed for mixes containing higher dosages due to dilution of hydration products. Dilution rate for SF concrete is much

less compared to AL concrete, for M5 concrete containing 20% SF, only a 3.3% strength decrement was observed to that of M4 containing 15% SF. Compressive strength of Ternary blended mixes M10, M11, M12, M13 and M14 were enhanced by 14.3%, 12.8%, 18%, 26.6 and 20.9% to that of the reference mix M1.

The 28-day compressive strength increment of 10%SF + 10% AL from the current study is higher compared to 10% strength increment from 10% RHA + 10% MK [31], 17.7% strength increment from 10% AL + 20% FA [32] and 7.15% strength increment from 30% Bagasse ash + 1.5% Nano silica [14]. Ternary mixes showed better performance in compression compared to binary mixes from the current study as well as from similar studies conducted by Biswas et al. [33] and Bhanja et al. [34], where SF binary mixes provided a maximum strength increment of 15% and 23.6% for 12% and 20% replacement of SF.

Ternary blending of SF and AL has positive interaction in terms of compressive strength. Higher replacement of AL is made possible with the addition of SF. Figure 5(c) shows the variation in strength with SF & AL dosage and curing age of ternary mixes. Figure 4. depicts the improvement in early strength compared to the later age strength of ternary blended concrete, mainly due to the presence of highly reactive AL. Even though, the dormant SF and AL components resulting from higher dosages will provide strength in later ages of concrete through ettringite formation, for early ages the dilution effect is less in ternary blended mixes compared to binary SF and AL mixes. Increase in the strength of ternary blended HPC is attributed to the presence of synergy between SF and AL.

4. 2. 2. Flexural Strength   The flexural strength of all the mixes is tested for a 28-day curing period and the results are shown in Figure 6. From the results, it is evident that the flexural strength of SF and AL blended binary concrete follows a similar course with the results of compressive strength and the results are in good agreement with earlier researches [35, 36]. Addition of pozzolanic materials into the concrete mix reduces calcium hydroxide concentration through the formation of secondary C-S-H gel, which then solidifies the interfacial bond between aggregates and paste in the matrix. Stronger the interfacial bond higher the flexural strength and resistance towards crack propagation. SF binary concrete increased the flexural strength furthermore compared to AL binary concrete.

M4 and M7 concrete with SF 15% and AL 10% showed increment in flexural strength of 30% and 26.2% in reference to the control mix M1. Ternary blended mixes M12, M13 and M14 with 20% replacement by weight of cement showed an increment of 25.8%, 43.1% and 31.9% compared to M1. Similar studies containing ternary blended mixes provided 10.69% increment in
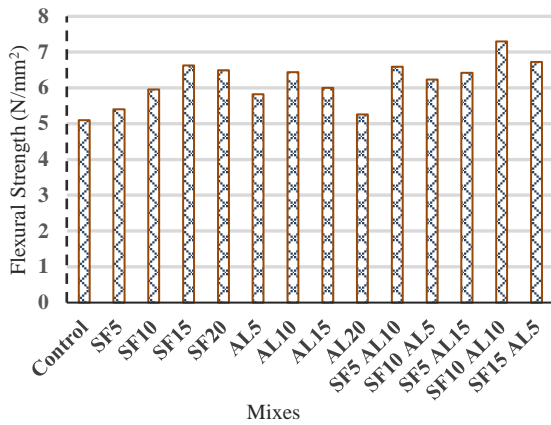
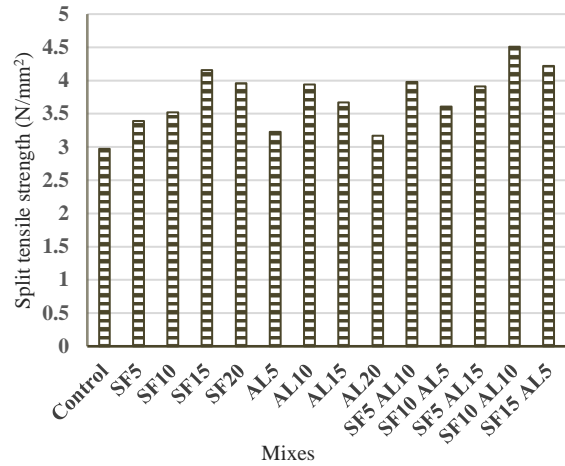**Figure 6.** Comparison of flexural strength test results

flexural strength resulting from 10% AL + 20% FA [32] and 31.2% increment resulting from 10% SF + 10% MK [10]. In the case of previous studies and the current study, ternary mixes provided better results in flexure compared to binary mixes. Mix containing a combination of 10% SF and 10% AL provided the maximum result. Failure modes of the samples in flexure are shown in Figure 7(b). Synergy was observed in all the ternary mixes with an increase in flexural values compared to their corresponding binary mix.

4. 2. 3. Split Tensile Strength   Even though concrete is purely designed to withstand compressive stresses, some tensile stresses may also develop due to temperature gradient, shrinkage and indirect tensile loads. Hence it is necessary to measure the tensile stress carrying capacity of the concrete elements. Figure 8 shows the split tensile strength (STS) test results at a curing period of 28 days, for all the mixes in the present study. From the results, it can be seen that, as the pozzolanic material content is escalated a significant improvement can be seen in both binary and ternary

Figure 8. Comparison of Splitting tensile strength test results

mixes with respect to control mixes. Similar to flexure strength, an increase in splitting tensile strength can be achieved through aggregate and matrix bond. Results of the splitting tensile strength test are in similar trends with the compressive strength values, the failure modes of the samples are shown in Figure 7(a).

Tensile strength increases with an increase in SF content up to 15%, after which, due to inadequate hydration products bond between matrix and aggregate weakens. M4 showed a tensile strength increment of 40% with reference to M1. Similarly, for AL binary mixes, STS increases up to a 10% replacement level after which powdered squashing is detected due to delayed crystallization and lack of hydration products. An increment in tensile strength of 32.6% for M7 is observed in reference to M1. In ternary blended concretes, dilution due to SF is balanced to some extent with the lime content present in AL, similarly, an increase in active silica content of SF made use of the Calcium oxide content in AL to produce effective C-S-H products. Ternary mixes M10 and M11 with 15% total replacement showed increments of 34% and 21.5% compared to M1. Ternary mixes M12, M13 and M14 with 20% total replacement showed increment of 31.6%, 51.8% and 42% compared to M1, which indicates its superiority over 16% increment from blending of 10% AL & 20% FA [32], 16.6 % increment resulting from 30% FA + 6% SF replacement [37] and 7.6% increment from 30% Bagasse ash + 1.5% Nano silica [14].
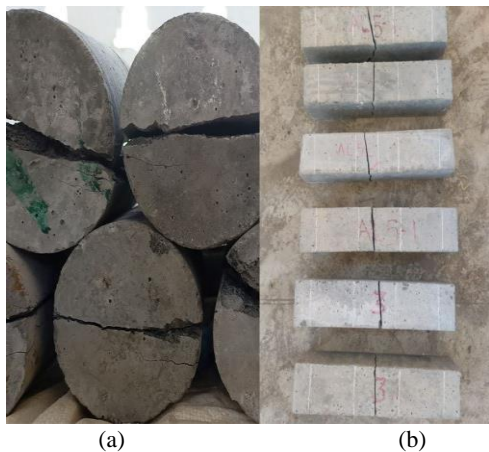
4. 3. Water Absorption   Percentage water absorption is the measurer of water absorbed by hardened concrete when immersed in water having temperature of 23ºC for a period of 48 hours, to that of oven-dried concrete sample for 24 hours. The test was carried out in a 100 X 100 mm cube sample taken out after 28 days of curing. Water absorption in concrete is a major durability

(a)   (b)

Figure 7. Failure modes a) Split tensile test b) Flexure test

test method, which is an indirect indicator of surface and internal pores. An increase in water absorption can damage the cover area of concrete and adversely affect the internal reinforcement [38]. Test has been carried out for all binary and ternary mixes and the results are compared in Figure 9. From the figure, a significant difference can be observed in the values for binary and ternary blended HPC. Binary mixes containing SF showed lower water absorption compared to AL binary mixes. Increase in alccofine percentage beyond 15% tends to increase water absorption, maybe due to the occupation of porous water in the AL particles. For SF binary mixes maximum and minimum decrement was observed for M5 and M1 with a percentile of 55.8 and 10.5. For AL binary mixes, maximum and minimum decrement was observed for M7 and M9 with a percentile of 52 and 4.9. In binary mixes, SF blended concrete prevents water absorption better than AL concrete. Ternary blended mixes M13 and M14 showed the lowest water absorption with a decrement of 64.6% and 65.7% compared to the control mix.

In general, the mechanical and durability properties of concrete have a higher correlation. Addition of SF and AL densifies the matrix through the reduction of pores which in turn reduces the ingress of water. The densification of pores is associated with the formation of secondary C-S-H crystals. The variation in the values of strength and water absorption for varying admixture proportions can be better ascertained from Figure 10. The graph shows similar trends with the work carried out by Al-Amoudi et al. [39] where an increase in strength resulted in reduced water penetration of plain and blended concretes.

4. 4. Empirical Relations

Empirical relations are necessary to determine the strength properties of concrete in the absence of another or inapplicability to perform the test [40, 41]. Standard codes and numerous researches have established empirical relations for normal/High strength concrete [42-50]. In this study, empirical relations to predict flexural and split tensile strength of HPC based on compressive strength are developed. From the tested results, it is observed that more data are inconsistent with the models proposed by standard codes and earlier studies, especially for ternary blended concrete. A similar observation has been pointed out by Abdul and Wong [51]. Hence re-evaluation of empirical relations is necessary for SCM replaced concrete both in binary and ternary forms. Empirical relations are developed in such a way that the deviation between experimental values and predicted values are much lesser, measured in terms of Integral Absolute Error (IAE).
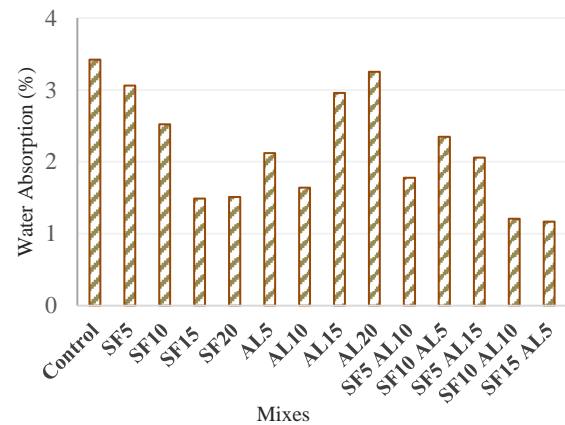
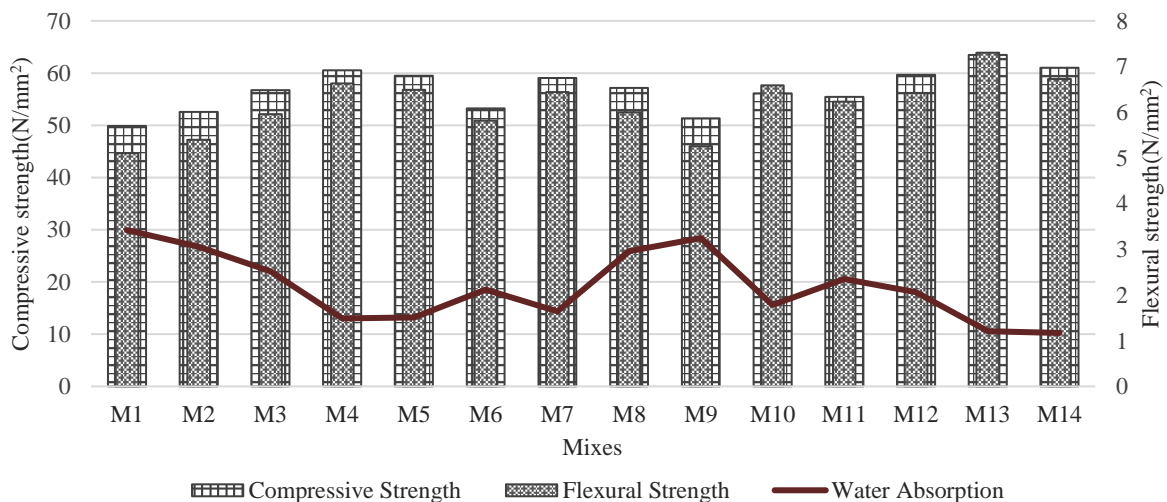**Figure 9.** Influence of Binary and Ternary mixes on Water absorption

Figure 10. Comparative analysis of strength and durability

$$IAE = \frac{\Sigma(Q-P)}{\Sigma P} \times 100\% \qquad (1)$$

where Q is the experimental value and P is the predicted value. Figure 11 shows the predicted values of flexural strength based on formulas proposed by various researchers and codes using compressive strength values from the current study. A general agreement is made on 0.5 as the power value to predict flexural strength with respect to compressive strength. From the figure, large deviations of predicted values from the experimental results are noticeable. The line of best fit indicates the power value of 1.54 due to the rise in the values of ternary blended concrete.

Even though the line of best fit has the maximum prediction accuracy, a formula has been proposed in agreement with the codal practices which has the least
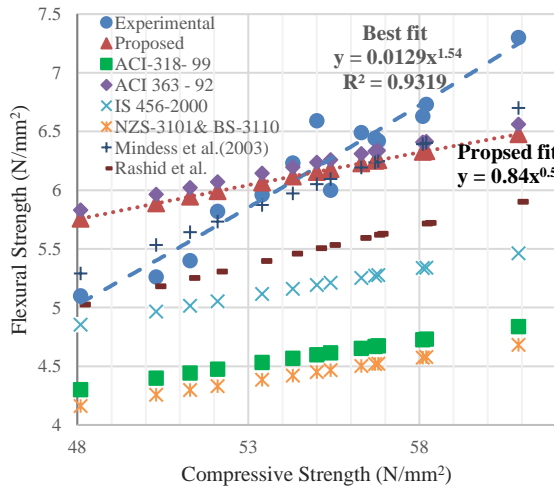
IAE of 0.47%. The proposed empirical relation for flexure strength is in close relation with ACI 363-92 (IAE = 2.07%) and Mindess et al. [34] (IAE = 2.33%). Table 4 displays the flexure strength prediction formulas and their corresponding IAE.

The predicted values of split tensile strength based on compressive strength from the current study using formulas proposed by various codes and researches are shown in Figure 12. The line of best fit has the power value of 1.83 unlike the more popular 0.5 and 0.66. This deviation in predicted values is majorly due to SCM replacement, especially in ternary forms where the positive interactions gave rise to higher strength values than that of binary mixes. The proposed empirical relation between STS and compression strength follows a power value of 0.7 with the least IAE of 1.55%. The proposed empirical relation for STS is in close relation with ACI 363-92 (IAE = 4.62%) and Rashid et al. [35] (IAE = 4.56%). Table 5 displays the STS prediction formulas and their corresponding IAE.

Figure 11. Relationship between Compressive strength and Flexural strength
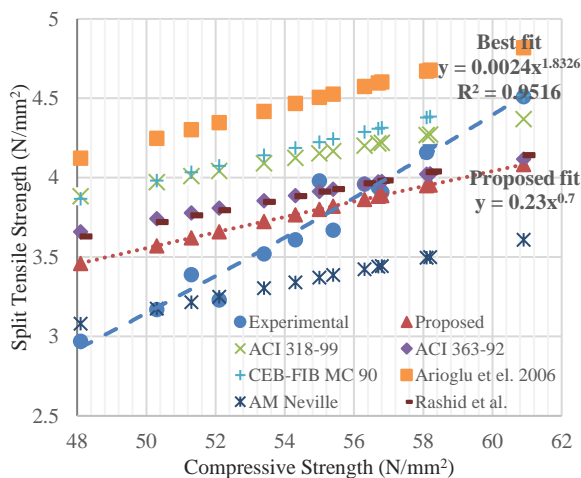
Figure 12. Relationship between Compressive strength and Split tensile strength

TABLE 4. Empirical relations between Compressive strength and Flexural strength

Code of practice/Researchers	Empirical Relation	Integral Absolute Error (IAE) %
ACI 318-99	$f_r = 0.62(f_c')^{0.5}$	25.65
ACI 363-92	$f_r = 0.94(f_c')^{0.5}$	2.07
IS 456-2000	$f_r = 0.7(f_c)^{0.5}$	16.06
NZS - 3101 & BS - 3110	$f_r = 0.6(f_c)^{0.5}$	28.05
Mindess et al. (2003)	$f_r = 0.11(f_c)$	2.33
Rashid et al. (2002)	$f_r = 0.42(f_c')^{0.68}$	11.04
Proposed	$f_r = 0.83(f_c)^{0.5}$	0.47

f_c – cube compressive strength, f_c' – cylinder compressive strength. Cylinder compressive strength assumed to be 0.8 times of cube compressive strength.

TABLE 5. Empirical relations between Compressive strength and Split tensile strength

Code of practice/Researchers	Empirical Relation	Integral Absolute Error (IAE) %
ACI 318-99	$f_{sp} = 0.56(f_c')^{0.5}$	11.02
ACI 363-92	$f_{sp} = 0.59(f_c')^{0.5}$	4.62
CEB - FIB MC 90	$f_{sp} = 0.3(f_c)^{0.66}$	12.86
Arioglu et al. (2006)	$f_{sp} = 0.32(f_c)^{0.66}$	20.38
AM Neville	$f_{sp} = 0.23(f_c)^{0.67}$	9.94
Rashid et al. (2002)	$f_{sp} = 0.47(f_c')^{0.56}$	4.56
Proposed	$f_{sp} = 0.23(f_c)^{0.7}$	1.55

f_c – cube compressive strength, f_c' – cylinder compressive strength. Cylinder compressive strength assumed to be 0.8 times of cube compressive strength.

4. 5. Synergy Assessment of Ternary HPC Mixes

Banthia et al. [52] have defined synergy as an increase in performance of the concrete mixture containing two materials to that of the combined individual performance of the material. Synergy assessment in fundamental mechanical properties is rarely discussed in past researches. In the case of ternary blended concrete, an assessment of synergy is necessary to evaluate the combined effect of cementitious materials, since two different SCMs are being used together. A formula has been worked out to evaluate synergy between SCMs in ternary mixes for compression, split tension and flexure.

$$\text{Synergy} = \frac{f_{(a+b)}}{[f_a + f_b]} - 0.5 \qquad (2)$$

where f is the strength of concrete in compression, split tension and flexure, a and b are percentages of SCMs used. The synergy equation estimates the combined effect of SCMs with respect to binary concrete, a positive value indicates the increased performance of ternary mix over two separate binary mixes.

Significant positive synergy is observed in early age compressive strength for all the ternary mixes. Ternary mix containing AL 10% + SF 5% and SF 10% + AL 5% showed zero synergy in later age strength of 28 and 45 days. In mixes M12, M13 and M14, only a slight increment in synergy is observed, and no negative synergy was noticed for any of the mixes in compression. Synergy values for ternary mixes in compression are shown in Figure 13. Mix 11 with SF 10% + AL 5% provided the least synergy in split tensile and flexure strength. Mix 13 with SF 10% + AL 10% provided a maximum of 8%, 10% and 9% increment in compression, split tensile and flexural strength synergy values. Figure 14 shows the synergy values of ternary mixes under indirect tensile stresses.

4. 6. Cost Analysis of SCM Replaced HPC

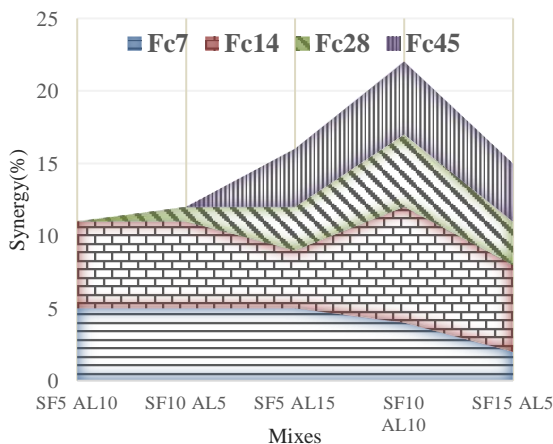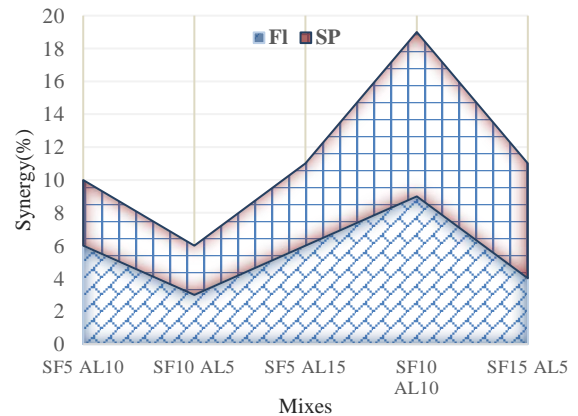Cost analysis of SCM replaced HPC with respect to normal

Figure 14. Synergy in Flexure and Split tensile strength

concrete can help contractors and customers better understand the additional benefits from the marginal cost increments. The increment spent for durability and strength will improve the service life of structures and can minimize the frequent repair cost due to the ingress of harmful agents. The cost of production of 1 m^3 of concrete for all the mixes from the current study is mentioned in Table 6. The unit prices taken as reference for all the raw materials are from the current market price (in Indian National Rupees, INR) of 2022, especially pertaining to Indian regions. The strength and durability increments of SCM concrete at the cost of small cost increments can be seen in Figure 15.

From the figure, a significant difference in the production cost is visible for SCM replaced concrete, with M5 having a higher cost in binary mix whereas M12 shows a higher cost for the ternary mix. All the SCM replaced mixes show increased production cost values compared to the control mix. The cost increment range varies from 2.23% to 9.7%, whereas the strength
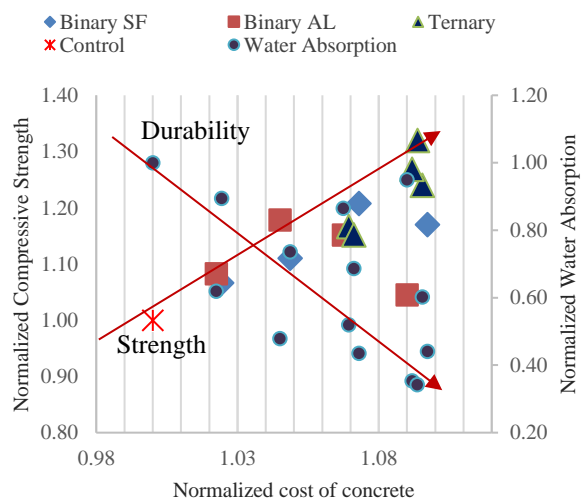
Figure 13. Synergy in Compressive strength

Figure 15. Cost analysis in terms of Durability and Strength

TABLE 6. Production cost of Binary and Ternary blended concrete

Mix Grade Material	Unit Price per kg (INR*)	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14
OPC	8	3600	3420	3240	3060	2880	3420	3240	3060	2880	3060	3060	2880	2880	2880
SF	16	-	360	720	1080	1440	-	-	-	-	360	720	1080	720	360
AL	18	-	-	-	-	-	405	810	1215	1620	810	405	405	810	1215
FA	1.05	702.4	660.4	618.4	576.4	534.4	672.5	642.7	612.7	582.8	600.7	588.5	546.5	558.7	570.7
CA	0.7	769.3	769.3	769.3	769.3	769.3	769.3	769.3	769.3	769.3	769.3	769.3	769.3	769.3	769.3
Mixing Water	0.02	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58
Electricity	-	600	600	600	600	600	600	600	600	600	600	600	600	600	600
Total (INR)	**-**	**5675.33**	**5813.3**	**5951.3**	**6089.3**	**6227.3**	**5870.4**	**6065.6**	**6260.7**	**6455.7**	**6203.6**	**6146.4**	**6284.4**	**6341.6**	**6398.7**

*INR – Indian National Rupee

increment varies from 5% to 32%. Previous researches in ternary blended concrete involving cost analysis in terms of strength shows cost variation of 0.85% to 1.025% with strength variation of 0.975% to 1.12% [31], whereas in this study a significant difference can be observed while comparing cost range and strength range. For an equal cost, ternary mixes M12, M13, and M14 showed better mechanical and durability performance compared to binary mixes M5 and M9.

5. CONCLUSIONS

Based on the results from experimental works and statistical analysis, the following conclusions can be drawn.

1. An attempt has been made to study the effects of ternary blending of SF and AL on the workability, mechanical and durability properties of HPC. Workability of ternary mixes were improved naturally to some extent due to ultrafine SF with rounded particle shape, in addition, superplasticizer was used to achieve a workable mix.

2. Binary SF mix M4 with 15% SF provided a maximum increment of 20.8% in compression, 30% in flexure and 40% in splitting tensile strength tests. After which dilution occurs gradually due to loss of hydration products. Binary AL mix M7 with 10% AL provided a maximum increment of 17.9% in compression, 26.2% in flexure, and 32.6% in splitting tensile strength. Components of AL are highly reactive, evident from its high early age strength development. Similarly, the dilution rate of

AL is much greater than SF, hence higher replacement levels are not recommended.

3. Ternary blended mixes showed improved load carrying capacity due to microstructural development through secondary C-S-H formation. All ternary mixes provided greater strength values compared to their binary counterparts. A mix containing SF 10% and AL 10% attained a maximum result of 26.6% in compression, 43.1% in flexure and 51.8% in splitting tensile strength.

4. No negative synergy was observed for any of the ternary mixes, however, mixes M10 and M11 exhibited zero synergy in later ages of 28 and 45 days compressive strength. Mix M11 and M13 showed the lowest and highest synergy in flexure and split tensile strength.

5. Higher replacement levels of SCMs, more than 20% total replacement should be explored since the dilution effect is less in ternary blended concrete compared to binary blend.

6. SF and AL densify the concrete, preventing harmful agents from entering through the pores. Water absorption test carried out in this study gave the lowest value for a mix containing SF 15% and AL 5%.

7. Empirical formulas from existing codes and previous researches to predict tensile strength from compression strength shows deviation in case of combinations of SCMs, the power value increases above 1 than the widely accepted 0.5. Hence re-evaluation of empirical relations is necessary for ternary blended concrete with the inclusion of a factor for synergy between the corresponding SCMs.

8. The new empirical relation proposed has the least Integral Absolute Error of 0.73% in predicting flexural strength and 1.55% in predicting split tensile strength.

9. Performance variation in ternary blended concrete is significantly greater compared to cost variation, hence will increase service life and reduce maintenance cost for structures in the long run.

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Persian Abstract

چکیده

این مقاله به بررسی مزایای بالقوه بتن سه‌گانه با کارایی بالا ترکیبی حاوی دوده سیلیس (SF) و آلکوفین (AL) به عنوان جایگزین‌های جزئی سیمان می‌پردازد. برنامه آزمایشی در مجموع شامل ۱۴ مخلوط با نسبت آب به اتصال دهنده ۴.۰ و درصدهای متفاوت (۰-۲۰٪) دوده سیلیس و آلکوفین هر دو به صورت دوتایی و سه تایی است. خواص تازه و سخت شده بتن بر اساس اسلامپ، مقاومت فشاری، مقاومت خمشی، مقاومت کششی شکافته و جذب آب مورد ارزیابی قرار گرفت. مخلوط های سه تایی حاوی SF و AL مقاومت فشاری بتن را ۱۴-۲۷٪ و مقاومت کششی را ۲۶-۴۳٪ در مقایسه با مخلوط مرجع افزایش دادند. افزایش استحکام اولیه برای همه مخلوط های سه تایی به وجود آلکوفین بسیار واکنش پذیر واکنش نسبت داده می شود. جایگزینی بیشتر از آلکوفین بیش از ۱۰٪ منجر به کاهش مداوم در استحکام به دلیل اثر رقیق شد، در حالی که برای دوده سیلیس، رقت استحکام به تدریج فراتر از جایگزینی ۱۵٪ بود. بسته بندی ذرات متراکم باعث کاهش جذب آب در مخلوط های سه تایی می شود. مخلوطی حاوی ۱۵ درصد SF و ۵ درصد AL 65.7 درصد کاهش جذب آب را در مقایسه با مخلوط مرجع نشان داد. ارزیابی هم افزایی برای تمام مخلوط های سه تایی انجام شد، نتیجه اوج برای مخلوطی حاوی ۱۰٪ SF و ۱۰٪ AL به دست آمد. بر اساس داده‌های تجربی، مدل‌های تجربی تهیه و با کدهای موجود و تحقیقات قبلی مقایسه شد. مدل های تجربی ارائه شده در این مطالعه دارای کمترین خطای مطلق انتگرال 0.47% (IAE) و ۱.۵۵٪ در پیش بینی مقاومت خمشی و مقاومت کششی شکافته بر اساس مقاومت فشاری بتن هستند.