Silicon (2020) 12:1949–1956
https://doi.org/10.1007/s12633-019-00324-0

ORIGINAL PAPER

Enhancing the Strength Properties of High-Performance Concrete Using Ternary Blended Cement: OPC, Nano-Silica, Bagasse Ash

P. Murthi[1] · K. Poongodi[1] · P. O. Awoyera[2] · R. Gobinath[1] · R. Saravanan[3]

Received: 15 August 2019 / Accepted: 7 November 2019 / Published online: 21 November 2019
© Springer Nature B.V. 2019

Abstract
This study determined the strength properties of high-performance concrete (HPC) produced using ternary blended cement, based on Nano-silica (NS) and bagasse ash (BA) addition to Portland cement. Several mix proportions, based on random mix design, were considered based on the substitution of constituent materials. Fine aggregate was comprised of 60% river sand and 40% recycled aggregate (RA), coarse aggregate used was crushed rock for the development of M50, M60 and M70 grades of concrete. The replacement of cement by BA causes slowdown initial strength development, but increased the setting time of concrete. In order to improve the performance of HPC at early stage, NS was considered as third admixture for developing ternary binder blend in the concrete. The effect of NS and BA on fresh and hardened HPC were investigated and presented. The results indicated that the incorporation of NS reduced setting time and increased the early age strength development significantly. Thus, it was concluded that the addition of NS with mean particle size of 12 nm is suitable as an additional binder for improving the early age performance of HPC.

Keywords Bagasse ash · Nano-silica · Early age properties · Recycled aggregate sand · High performance concrete

1 Introduction

High performance concrete (HPC) is a concrete mixture that exhibit high workability, strength and durability features. In recent years, there are considerations to develop HPC using alternative materials. In such mixtures, HPC contains one or more of cementitious materials such as fly ash, silica fume or ground granulated blast furnace slag along with superplastizer. The supplementary cementitious materials are generally pozzolanic in nature and when present in mixture, strength development is expected to continue for a longer time than the case of conventional concrete. The fresh properties of HPC are also expected to vary, owing to the ingredient and supplementary cementitious materials used in the concrete. Fly ash (FA) and Rice husk ash (RHA) is a well-known supplementary cementitious materials widely used in HPC [1, 2]. Concrete containing FA has shown slow rate of strength development at early ages compared to normal concrete [1]. Due to its pozzolanic character of sugarcane bagasse ash (BA), other research are aimed at the utilization of ground BA as a supplementary cementitious in concrete [3]. A high early strength can be achieved if up to 20% of cement is replaced with the well burnt BA, without causing any adverse effect on the desirable properties of concrete [4].

Also, there is need for rationalizing the utilization of aggregates in concrete. The collection of sand from the river bed leads to the economical imbalance, particularly in the agriculture sector along with the strict local body legislation in India [5, 6]. As an alternate to the natural sand, demolished concrete waste, used as recycled aggregate (RA), is considered instead of sand, however the compatibility has to be investigated. According to previous report, the addition of RA sand increased the water demand due to the absorption behavior, and reduced the workability and setting time of concrete [7].

Now-a-days the Nano-technology plays a vital role in the development of new products. The availability of suitable nano materials like nano-silica (NS) and nano-fibers has enabled their use for improving the properties of concrete. The

✉ P. O. Awoyera
paul.awoyera@covenantuniversity.edu.ng

1 Department of Civil Engineering, S R Engineering College, Warangal, India

2 Department of Civil Engineering, Covenant University, Ota, Nigeria

3 Department of Civil Engineering, Navodaya Institute of Technology, Raichur, India

application of NS in concrete and mortar are reported in the recent years that NS enhanced the strength properties of the concrete [8–10]. The higher strengths of concrete of those mixtures was attributed to the reduction of pore size [1], accelerated cement hydration [11], improving the intermediate zone [9] and larger specific surface area [10]. All these, eventually enhance the durability of concrete [1]. The incorporation of NS reduces the setting time of concrete containing slag [12]. Also, the addition of NS to the mixture caused a slight reduction in both the initial and final setting time of pastes. Whereas, the difference between the initial and final setting time decreased with increasing NS content [13]. More also, the presence of NS particle in fly-ash blended concrete has been reported to improve the early age strength of concrete [14].

So far in the open literatures, numerous studies have considered the use of NS as ingredients/admixtures in development of cementitious mixtures. However, the present study tends to improve on the existing studies, by exploring the influence of NS on the early age performance (homogeneity, setting time and strength development) of HPC, as an attempt to compensate the effects of adding RA-sand in HPC. The relationship between setting time and 28 days strength of RA-sand based BA blended HPC was also developed.

2 Materials and Method

2.1 Materials

A grade 53 Ordinary Portland cement confirming to IS 12269 [15], ground BA and NS (average particle size of 12 nm) were used as binder in this investigation. The Chemical compositions and Physical properties of all these materials are mentioned in Tables 1 and 2, respectively. Local river sand was used as fine aggregate. Its fineness modulus and specific gravity is 2.67 and 2.71, respectively. RA-sand derived from demolished concrete was used after it has been processed to similar size as conventional sand (<4.75 mm). The specific gravity and fineness modulus of RA-sand is 2.64 and 2.69, respectively. The crushed granite coarse aggregate with a

Table 1 Chemical composition of cementitious materials

Chemical Composition (%)	OPC	Bagasse ash	Nano-silica
CaO	61.6	1.78	–
SiO_2	22.4	51.85	>98.5*
Al_2O_3	5.2	25.31	–
Fe_2O_3	3.8	11.5	–
MgO	1.7	1.5	–
LoI	2.3	2.4	–

Table 2 Physical properties of cementitious materials

Physical properties	Portland cement	Bagasse ash	Nano-silica
Initial setting time (min)	75	–	–
Final setting time (min)	235	–	–
Specific gravity	3.15	2.52	2.28*
Specific surface area (m^2/kg)	295	440	201
Average particle size	27.8 (μm)	27.2(μm)	12 nm
Comp. strength (28 days) (MPa)	58.5	–	–

*Information provided by the supplier

maximum size of 20 mm was used for concrete mixtures. The fineness modulus and specific gravity of the coarse aggregate were 7.19 and 2.78 respectively. Both fine aggregate and coarse aggregate complied with the requirements of IS: 383–2016. The results of grain size distribution (zone – II) of river sand and the combination of 60% river sand and 40% RA-sand are shown in Fig. 1.

2.2 Design of the Experiment

The 40% of the natural sand was replaced by RA-sand in this investigation. BA and NS were employed by weight of cement for achieving M50, M60 and M70 grade HPC mix and concrete mixtures are designated accordingly.

2.3 Mix Proportions

The trial mix proportion of M50, M60 and M70 grade HPC was initially performed. The BA content are varying from 28% to 32% for getting blended concrete and NS content varies up to 2% in the mix proportions in this experimental investigation. As per the preliminary studies, the sand content was replaced by RA-sand at the level of 40% and coarse aggregate content was slightly adjusted in order to maintain the workability of concrete. The target

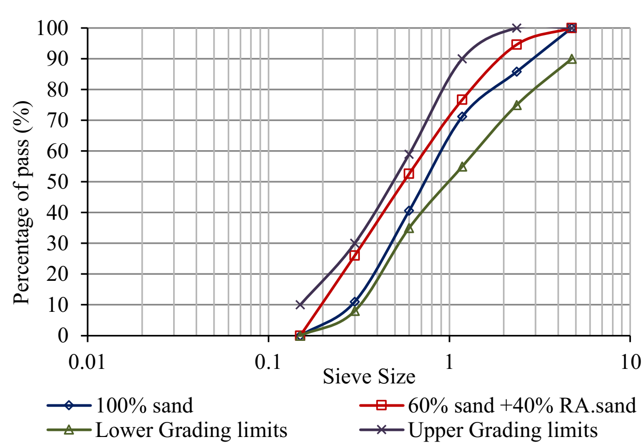

Fig. 1 Grain size distribution of river sand and RA sand

slump value has been fixed between 150 to 200 mm and hence the suitable amount of superplastizer was added during mixing. After various trials were conducted for predicting the appropriate mix proportioning, the final mix proportions of HPC used in this study is as presented in Table 3.

2.4 Experimental Procedure

Concrete mixtures were prepared at the laboratory temperature condition 23 °C to 28 °C. In order to ascertain the homogeneity of concrete, the workability of fresh concrete was evaluated by slump test. The setting time of fresh concrete was found by the penetration resistance test using Penetrometer as per [16]. The penetration resistance curve was prepared against elapsed time. From the penetration resistance curve, the time required to reach the resistance equal to 3.5 MPa is read on the x-axis which gives the initial setting time and the penetration resistance of 27.6 MPa gives the final setting time of concrete. For each type of concrete, three concrete cube specimens of 150 × 150 × 150 mm size and three-cylinder specimens of 150 mm diameter and 300 mm long were tested for finding compressive strength and splitting tensile strength respectively at each curing period of 3, 7, 14 and 28 days. The relationship between final setting time and the 28 days compressive strength of corresponding HPC were developed.

3 Results and Discussion

3.1 Fresh Concrete Properties

3.1.1 Workability of HPC

The slump values of the HPC is shown in Fig. 2. The dosage of the superplastizer (ranging from 1.42 to 2.97 l/m^3) in all the concrete mixtures was adjusted to produce the slump value of 150–180 mm. The addition of RA-Sand and NS caused marginal reduction in slump value, and this may be as a result of variation in the particle sizes and textural characteristics of RA-sand and more specific surface area of NS particles. Hence, the dosage of the superplastizer increased in concurrence with RA-sand due to slightly higher water absorption behavior of RA-sand than the river sand and more water demand of NS particles. A similar observation was reported for a concrete incorporating ceramic as coarse aggregate, where the higher water absorption capacity of ceramics slightly influenced the flow ability of the concrete [17].

3.1.2 Setting Time of HPC

The penetration resistance curves for finding the initial and final setting time of BA based HPC without NS designated as M50NS0, M60NS0 and M70NS0 are shown in Fig. 3. The initial and final setting time of M50NS0 was 462 and 572 min, respectively. From the penetration resistance curve. Similarly, the initial setting time of M60NS0 and M70NS0 was 415 and 368 min, respectively and the final setting time of M60NS0

Table 3 Mix Proportions for HPC

Mix designation	Ingredient (kg/m^3)						w/cm	SP (l/m^3)
	Cement	BA	NS	Sand	RA-Sand	CA		
M50NS0	420	160	–	468	312	900	0.40	1.42
M60NS0	434	186	–	456	304	890	0.39	2.10
M70NS0	442	208	–	444	296	870	0.38	2.51
M50NS0.5	417	160	2.9	468	312	900	0.40	1.48
M60NS0.5	431	186	3.1	456	304	890	0.39	2.12
M70NS0.5	439	208	3.3	444	296	870	0.38	2.55
M50NS1	414	160	6.0	468	312	900	0.40	1.52
M60NS1	428	186	6.2	456	304	890	0.39	2.20
M70NS1	436	208	6.5	444	296	870	0.38	2.69
M50NS1.5	411	160	9.0	468	312	900	0.40	1.60
M60NS1.5	425	186	9.3	456	304	890	0.39	2.31
M70NS1.5	432	208	9.8	444	296	870	0.38	2.97
M50NS2	408	160	12.0	468	312	900	0.40	1.65
M60NS2	422	186	12.4	456	304	890	0.39	2.37
M70NS2	429	208	13.0	444	296	870	0.38	2.99

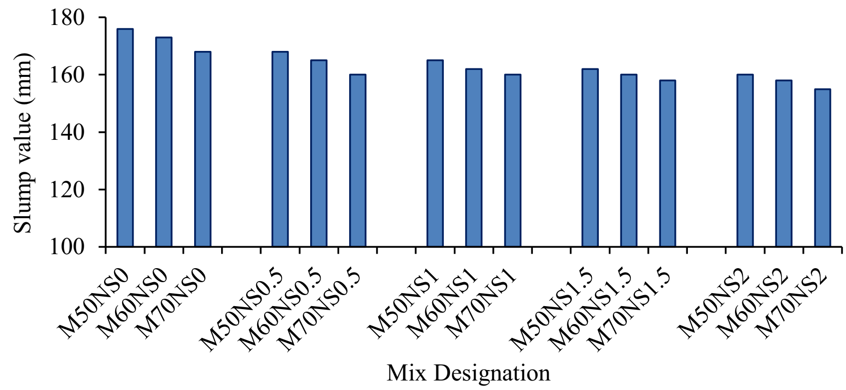

Fig. 2 Effect of mixing NS on Slump value of BA blended HPC

and M70NS0 was found as 552 and 524 min respectively. There was also a decreasing trend in both the initial and final setting time as the cement content was increased in mixture. The retarding in setting time of concrete can be mainly attributed to the amount of cement present in the concrete for reaction during initial period [18]. Effects of the substitution of NS on the initial and final setting time of BA blended HPC in comparison with 0% NS are shown in Fig. 4. The substitution of NS content reduces the initial setting time. The presence of NS particles in the concrete reduces paste liquidity and decreases setting time [13]. From the Fig. 4, the significant reduction in initial setting time of BA based HPC was observed due to the addition of 0.5% NS.

The addition of NS up to 1.5% caused a reduction in the initial setting time of the concrete. However, the addition of 2% NS did not affect the initial setting time. The marginal reductions in final setting of HPC samples were noticed due to the substitution of NS compared to the setting time of HPC without NS. From Fig. 4, it was also observed that adding more than 1.5% of NS increases the initial setting time due to further increasing the surface area and more water demand in the concrete. Similar to the initial setting time, the addition of more than 1.5% NS did not affect the final setting time due to the presence of un-hydrated cementitious

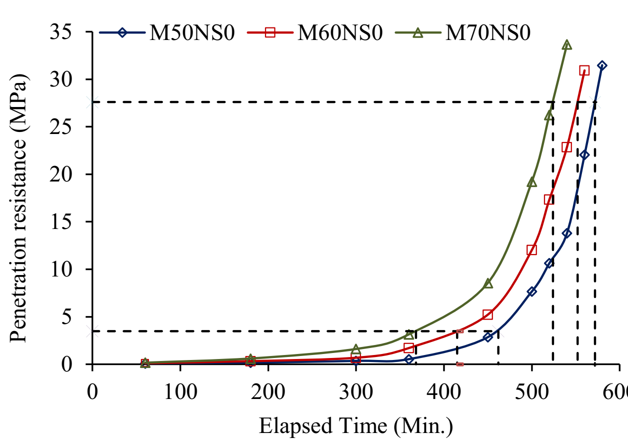

Fig. 3 Penetration resistance curve of HPC specimens without NS

materials. The reduction of setting time up to 1.5% NS concrete may be related to the finer particle size and higher specific surface area of the NS particle compared to the other cementitious material presents in the concrete which increases the initial hydration.

3.2 Compressive Strength Development of HPC

The effect of mixing NS on the compressive strength development of BA blended HPC at the early ages (1 day, 3 days and 7 days) and maturity (28 days) is shown in Fig. 5. Test results indicate that the NS caused improvement in the compressive strength of HPC specimens at the early ages. By investigation, it has been observed that the percentage increase of compressive strength of M50 grade HPC specimen is 38.83 and 80.07% at the age of 1 day by adding 0.5% and 1.0% NS, respectively. Similar kind of improvement has also been observed in M60 and M70 grade concrete. The substitution of NS up to 1.5% produced higher compressive strength values than those obtained when 0.5, 1 and 2% NS were used. Practically, it is an indication that optimum pozzolanic reactivity of NS is achieved at 1.5% substitution. The Fig. 4b has also been witnessed that the percentage increase of compressive strength of HPC up to 1.5% NS at the age of 3 days. However, the rate of growth of compressive strength at 7 days curing starts decreased when compared to corresponding specimens of 1 day and 3 days curing due to the completion of early reactions of NS particles. The 7 days compression test revealed that BA and NS addition caused improvement in strength of all three grades of concrete considered in this study. This performance could be a function of secondary reaction initiated by the presence of BA along with the remaining NS particles present in concrete. The increased early strength with the incorporation of nano size silica might be attributed to the high specific surface areas that increased the rate of hydration and pozzolanic reaction. The results are consistent with findings by Qing et al. [10]. Interestingly the marginal reductions in rate of strength development in all the designated concrete specimens were noticed after the

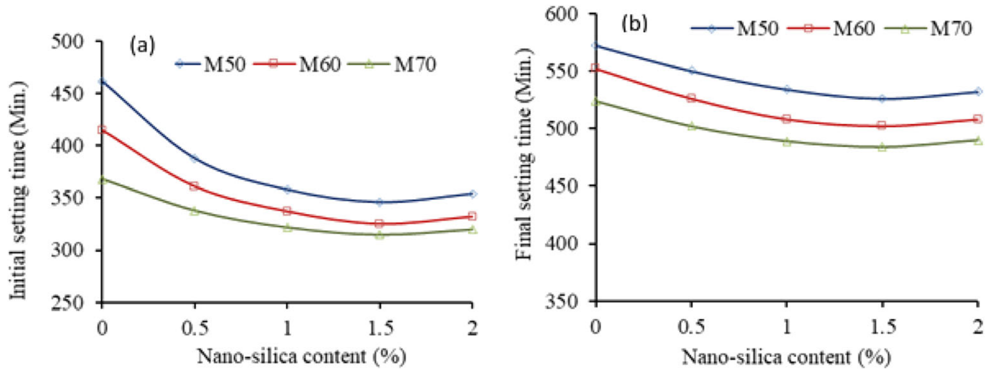

Fig. 4 Effect of mixing NS on Setting Time of BA blended HPC (**a**) Initial setting time (**b**) Final setting time

substitution of 2.0% NS. From the results, it has been observed that the presence of NS increases the rate of strength development of BA blended HPC during the early curing period and the presence of BA contribute the improvement of compressive strength of HPC during later age due to its secondary reaction (evident by the higher silica contents of BA-51.85 and NS- 98.5). Also, there is certainly slower hydration of Portland cement in the early ages, due to the addition of BA and NS.

3.3 Splitting tensile strength of HPC

The effect of mixing NS on the splitting tensile strength of HPC at 3 days, 7 days and 28 days are shown in Fig. 6. Test results indicated significant improvement in the splitting tensile strength of HPC specimens during at early age. By investigation, it has been observed that the percentage increase of splitting tensile strength of M50 grade HPC specimen is 31.96% at the age of 3 day by adding 1.5% NS. From Fig. 6a, similar kind of improvement has also been observed in M60 and M70 grade concrete. The Fig. 4b has also been observed that the percentage increase of splitting tensile strength of HPC up to 1.5% NS at the age of 7 days. The substitution of NS up to 1.5% can enhance the splitting tensile strength of concrete in all the grades of concrete considered in this investigation. This improvement during the early age witnessed the strength development during early age due to the higher specific surface area of NS particles which develops the bond

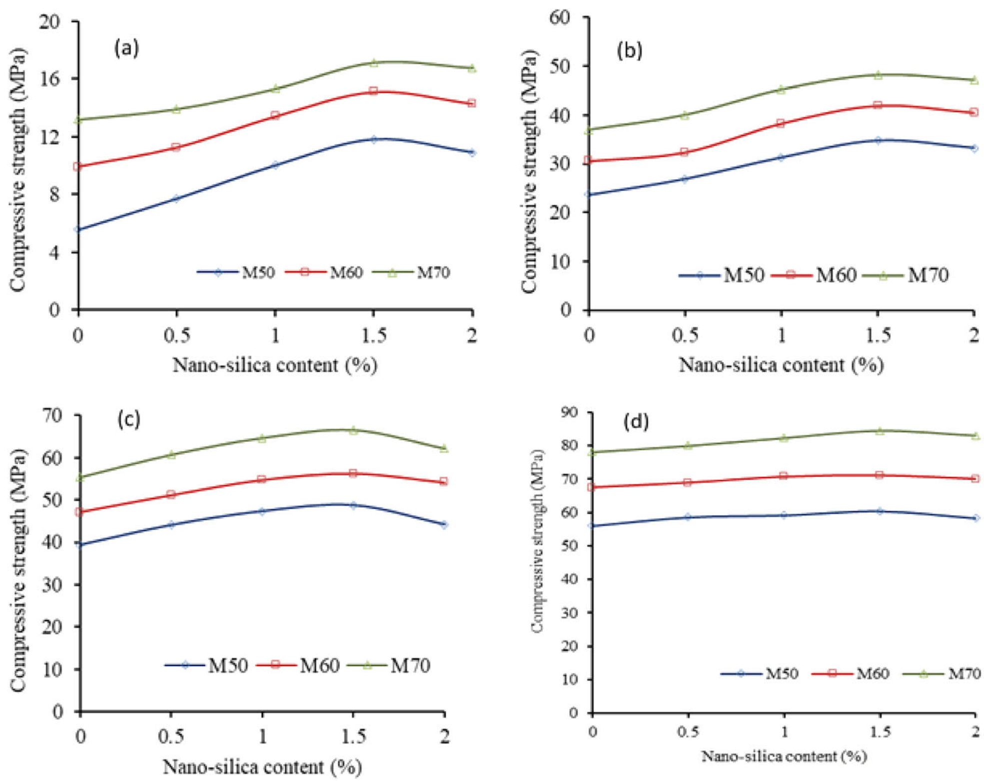

Fig. 5 Effect of mixing NS on the Compressive Strength Development of BA blended HFC. (**a**) 1 day curing (**b**) 3 days curing **c**) 7 days curing (**d**) 28 days curing.

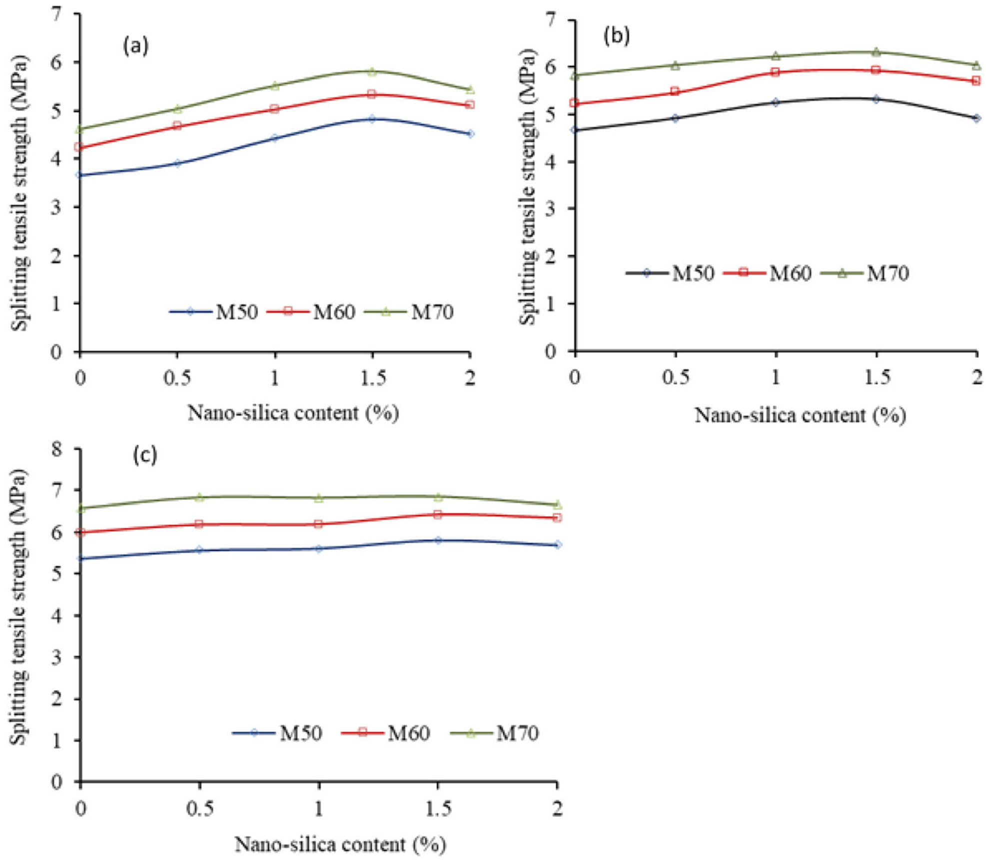

Fig. 6 Splitting tensile strength of NS blended HFC (**a**) 3 days curing (**b**) 7 days curing (**c**) 28 days curing

between the aggregate phase and paste phase. The splitting tensile strength at 28 days was observed higher order but the rate of improvement due to the addition of NS was observed as lesser than the early age results due the maximum strength attainment of BA blended HPC.

3.4 Relationship between Compressive Strength and Splitting Tensile Strength

The data plotted in Fig. 7 depicts the model equation that relate the compressive strength and splitting tensile strength of HPC with NS and RA-sand at early curing periods and 28 days curing are shown in Fig. 7. It was found that the relationship at early age as:

$$f_t = 0.7756(f_{ck})^{0.502} \quad (1)$$

Based on these data, it is clear that the early age strength of HPC having NS was improved than that obtained using the IS:456 [19] code equation:

$$f_t = 0.7(f_{ck})^{0.5} \quad (2)$$

The ACI 318 [20] expresses the relationship between modulus of rupture (f_r) and the compressive strength (f_{ck}) as:

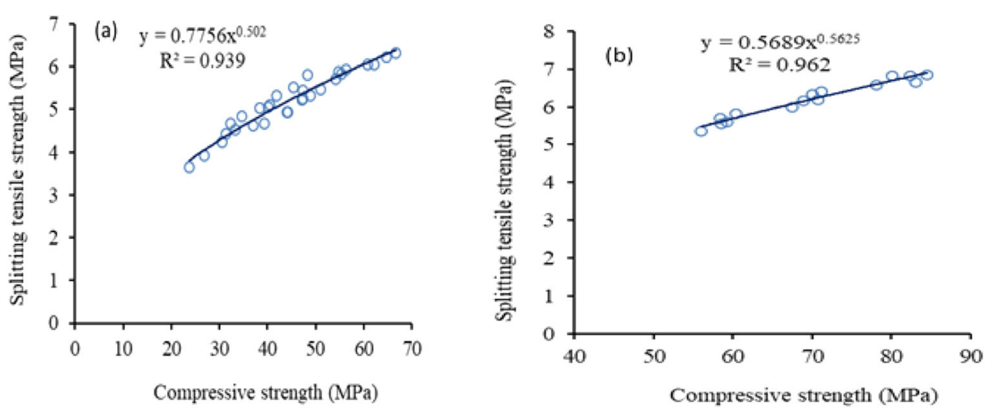

Fig. 7 Effect of NS on relationship between Compressive strength and splitting tensile strength (**a**) Early age (3 and 7 days) relationship (**b**) 28 days relationship

$$f_r = 0.56(f_{ck})^{0.5} \quad (3)$$

The substitution of NS was evidently shown by the equation that the relationship between the early age compressive strength and splitting tensile strength are comparable with the various code provisions. Interestingly, the 28 days cured HPC specimen does not provide the relationship specified in the code. In a related study, Oluokun et al. [21] has shown that model equation for compressive strength and splitting tensile strength could not be proportional to 0.5 power, but their study revealed that tensile strengthcould be proportional to 0.79 power. Athi Gajendran et al. 2015 predict the relationship with Metakaolin and Silica fume based ternary blended concrete as:

$$f_t = 0.689(f_{ck})^{0.401} \quad (4)$$

Hence the generally recognized 0.5 power relationship as per IS: 456–2000 and ACI code was examined and suggested a new relationship for NS based BA blended HPC. This study has revaleaed the model equation relating the compressive strength and splitting tensile strength of HPC at 28 days as: follows:

$$f_t = 0.5689\ (f_{ck})^{0.5625} \quad (5)$$

4 Conclusion

The study focused on the enhancement of the strength properties of high-performance concrete using ternary blended cement, based on Nano-silica (NS) and bagasse ash (BA) addition to Portland cement. The following conclusions were drawn from the study:

- In order to maintain the workability in the range of 150 mm – 180 mm in RA-sand and NS and BA blended HPC, the dosage of the superplastizer increased due to slightly higher water absorption behavior of RA-sand than the river sand and more water demand of NS particles.
- The initial and final setting time decreased up to the addition of 1.5% NS and this was sustained when NS content was increased to 2%.
- The HPC incorporating up to 1.5% NS exhibits good strength, with a percentage strength increment, particularly for M50 grade, at 38.83 and 80.07% at the age of 1 day by adding 0.5% and 1.0% NS, respectively. Also, strength results at 3 and 7 days also increased as a result of 1% NS addition. The substitution of NS up to 1.5% enhanced the compressive strength of concrete more than 100% in all the grades of concrete considered in this investigation.
- Similarly, the percentage increment in splitting tensile strength for M50 grade of HPC specimen was 31.96% at the age of 3 day by adding 1.5% NS. The substitution of NS up to 1.5% can enhance the splitting tensile strength of concrete in all the grades of concrete considered in this investigation.
- Based on the model equations derived to relate the compressive strength and splitting tensile strength of BA based HPC with NS at 3 days and 7 days, it could be deduced that the early age strength of HPC with NS was improved than the value obtained using IS: 456–2000 code relationship.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

1. Li G (2004) Properties of high-volume fly ash concrete incorporating nano-SiO_2. Cem Concr Res 34:1043–1049. https://doi.org/10.1016/j.cemconres.2003.11.013
2. Amudhavalli NK, Murthi P (2014) Effect of replacement of cement by Rice husk ash and silica fume with polypropylene fibre on the property of impact resistance. Aust J Basic Appl Sci 8:122–127
3. Anandaraj S, Rooby J, Awoyera PO, Gobinath R (2019) Structural distress in glass fibre-reinforced concrete under loading and exposure to aggressive environments. Constr Build Mater 197:862–870. https://doi.org/10.1016/j.conbuildmat.2018.06.090
4. Thirumalai RK, Murthi P (2015) Bagasse ash and rice husk ash as cement replacement in self-compacting concrete. Građevinar 67:23–30
5. Murthi P, Awoyera P, Selvaraj P, et al (2018) Using silica mineral waste as aggregate in a green high strength concrete: workability, strength, failure mode, and morphology assessment. Aust J Civ Eng 0:1–7 . doi: https://doi.org/10.1080/14488353.2018.1472539
6. Selvaraj KP, Murthi P, Gobinath R, Awoyera PO (2018) Eco-friendly high strength concrete production using silica mineral waste as fine aggregate – an ecological approach. Ecol Environ Conserv 24:909–915
7. Abdel-Hay AS (2017) Properties of recycled concrete aggregate under different curing conditions. HBRC J 13:271–276. https://doi.org/10.1016/j.hbrcj.2015.07.001
8. Ltifi GA, Mounanga P, Khelidj A (2011) Experimental study of the effect of addition of nano-silica on the behaviour of cement mortars Mounir. Procedia Eng 10:900–905. https://doi.org/10.1016/j.proeng.2011.04.148
9. Senff L, Labrincha JA, Ferreira VM et al (2009) Effect of nano-silica on rheology and fresh properties of cement pastes and mortars. Constr Build Mater 23:2487–2491. https://doi.org/10.1016/j.conbuildmat.2009.02.005
10. Qing Y, Zenan Z, Deyu K, Rongshen C (2007) Influence of nano-SiO_2 addition on properties of hardened cement paste as compared with silica fume. Constr Build Mater 21:539–545
11. Nanthagopalan P, Santhanam M (2011) Fresh and hardened properties of self-compacting concrete produced with manufactured sand. Cem Concr Compos 33:353–358. https://doi.org/10.1016/j.cemconcomp.2010.11.005

12. Berra M, Carassiti F, Mangialardi T et al (2012) Effects of nanosilica addition on workability and compressive strength of Portland cement pastes. Constr Build Mater 35:666–675. https://doi.org/10.1016/j.conbuildmat.2012.04.132
13. Pourjavadi A, Fakoorpoor SM, Khaloo A, Hosseini P (2012) Improving the performance of cement-based composites containing superabsorbent polymers by utilization of nano-SiO_2 particles. Mater Des 42:94–101. https://doi.org/10.1016/j.matdes.2012.05.030
14. Kawashima S, Hou P, Corr DJ, Shah SP (2013) Modification of cement-based materials with nanoparticles. Cem Concr Compos 36:8–15. https://doi.org/10.1016/j.cemconcomp.2012.06.012
15. IS 12269 (1987) Specification for 43 grade ordinary Portland cement. Indian Stand
16. ASTM C403 / C403M-16 (2016) Standard test method for time of setting of concrete mixtures by penetration resistance, ASTM International, West Conshohocken, PA. https://www.astm.org
17. Awoyera PO, Ndambuki JM, Akinmusuru JO, Omole DO (2016) Characterization of ceramic waste aggregate concrete. HBRC J. https://doi.org/10.1016/j.hbrcj.2016.11.003
18. Aydin AC, Gül R (2007) Influence of volcanic originated natural materials as additives on the setting time and some mechanical properties of concrete. Constr Build Mater 21:1277–1281. https://doi.org/10.1016/j.conbuildmat.2006.02.011
19. IS 456 (2000) Plain and Reinforced Concrete - Code of Practice, Indian standard code, India
20. ACI 318M (1995) Building Code Requirements for Structural Concrete & Commentary, AmericanConcrete Institute, Farmington Hills, Michigan, USA
21. Oluokun FA, Harold J Deatherage EGB Splitting Tensile Strength and Compressive Strength Relationships at Early Ages. ACI Mater J 88. https://doi.org/10.14359/1859

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.