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Development of Optimum Aggregate Mix for High Strength Concrete with Metakaolin as Admixture

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***Abstract*: In the development of high strength concrete, aggregate proportioning and aggregate sizes have been significant factors in the determination of strength of concrete. This has resulted in the development of mix design methods that yield the requisite aggregate size usage in the production of concrete. The particle packing model mix design which is based on continuous gradation of aggregate size is a mix design approach that is aimed at obtaining optimum aggregate mixture for varying aggregate sizes in obtaining target strength of concrete. In this study, the particle packing model mix design was implemented to produce a high strength concrete through experimental evaluations of workability and mechanical performances. Also, the influence of metakaolin on the strength and workability performances were evaluated. Concrete samples were produced using metakaolin as partial substitutes for cement in percentages of 0, 5, 10, 15 and 20. Experimental tests implemented on concrete include slump test for workability assessment, compressive strength test, splitting tensile strength test and flexural strength test for mechanical properties. Test results showed that the adopted mix design was reliable for the production of high strength concrete. The workability and mechanical performance of high strength concrete were improved by the inclusion of metakaolin into the concrete matrix. Optimum dosage of metakaolin were obtained at 15% inclusion.**

***Keywords*: particle packing model, high strength concrete, mechanical performance, metakaolin, mix design, partial substitution.**

1. Introduction

Concrete has become one of the most widely used construction material resulting in the development of varying forms of concrete such as high strength concrete with desired properties such as high mechanical properties, good ductile performance, fire resistance, less environmental impacts and good durability (Aslani et al, 2020). High strength concrete presents advantage of high compressive strength, high durability, reduced durability and good workability. However, high strength concretes are more brittle compared to normal strength concrete. They are more susceptible to crack development and brittle failure (Artcin, 2003; Kjellsen et al, 2000).

Mix design approach has been observed to be a critical factor affecting the mechanical and durability performance of high strength concrete. Mechanical performances of concrete have been shown to be highly affected by the availability of voids. The void volume in concrete can reduce drastically the mechanical performance of concrete. Hence, it is necessary to develop concrete mixes with methods that focus on minimizing these voids. Particle parking model mix design has been developed as a method of reducing voids in concrete matrices. This utilizes various aggregate sizes with finer particles to minimize voids.

From survey of literature, studies have been carried out using particle parking model for mix design have used very few numbers of aggregate sizes with maximum three aggregate sizes. Therefore, minimizing the knowledge on adequate utilization of more aggregate sizes in the preparation of concrete with required high performance. Therefore, this study shall be implemented to study the mechanical performance of high strength concrete with more aggregate sizes using continuous gradation of aggregate to obtain optimum aggregate quantity for maximum parking density.

The structural performances of high strength concrete have been examined by various researchers ranging from physical, fresh, mechanical to durability properties using different methodologies of mix designs. Properties of high strength concrete produced with different kinds of concrete materials and admixtures have been evaluated. Vejmelkova et al (2009) carried out an investigation into the mechanical and durability performances of high strength concrete containing low amount of slag (10% by weight) as partial replacement for cement. The mechanical and durability properties were very similar to those of control specimen (samples without slag). The liquid water transport parameters were observed to be bettered by the inclusion of slag.

The effects on mechanical and durability properties of high strength concrete by nano particles were investigated by Shekari & Razzaghi (2011). Concrete samples were prepared with Portland cement and metakaolin as basic binders in ratios of 85% to 15% respectively. At constant volumes, nano particles of ZrO_2, TiO_2, Al_2O_3 and Fe_3O_4 were added to the concrete mix. All concrete samples were cured in water and

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subjected to compressive and indirect tensile strength tests for mechanical tests and chloride penetration test and water absorption tests for durability. Test results obtained showed that all nano-particles examined had positive impacts on mechanical and durability properties of HSC with the best performance from nano-Al_2O_3.

The above papers were implemented to examine the effects of aggregates content on the performance of high strength concrete. Some studies have been implemented to examine the effect of mix design approach on the performance of high strength concrete.

Pan et al (2020) explored an optimized gradation design method to reduce the influence of reclaimed asphalt pavement (RAP) gradation variability on the performance of recycled asphalt mixture. Recycled asphalt mixture segregation with high RAP contents in transportation and construction were evaluated first, for the variability analysis in accordance with the fractal dimension (FD) in fractal theory. An FD-based gradation segregation model was established to evaluate the variability of RAP gradation. RAP contents of 20%, 35% and 50% was analyzed respectively and it was found that the higher the amount of RAP in RAM, the more serious the degree of segregation. To ensure the performance of RAM with high RAP contents, it is necessary to reduce the variability of RAP gradation. The optimized design method for increasing the passing rate was based on Mohr-coulomb theory and was confirmed as reasonable and effective.

Ren et al (2021) investigated the effect of different size aggregates on the air void ratio and macroscopic aggregate bearing capacity, to present an aggregate gradation with a strong aggregate structure, using a modified triaxial test and discrete element method (DEM) simulation. Laboratory tests show that the proposed gradation provides an improved pavement performance for porous asphalt mixture. Moreover, strength mechanisms of aggregate structure in porous mixture are revealed from a view of the mesoscopic aggregate contact force composition using DEM simulations considering aggregate irregularity.

The above mix design approaches have demonstrated the significant impact on the strength and durability performance of high strength concrete. However, the particle packing model which are implemented based on the concept of void volume reduction or increment in the packing density of concrete mixes are important mix design approach that are implemented to improve the mechanical and durability performance of high strength concrete. It is a concept of mix design where finer particles are introduced into concrete matrices to reduce voids.

A comparative study on the particle packing method mix design and conventional mix design method was carried out by Sunayana & Barai (2017). Both natural aggregate concrete and recycled aggregate concrete examined were prepared with fly ash partial substitute for cement. To achieve the design for PPM mix proportioning, 18% and 28% of cement was replaced with 20% and 30% fly ash at water binder ratio of 0.45. Mechanical properties of concrete were examined. Results obtained showed that the compressive strength, flexural strength and elastic modulus of RAC were improved better with PPM than with conventional method while the tensile strength was less. The researchers recommended based on their results that PPM should be implemented for RAC concrete incorporating fly ash up to 30% cement replacement.

Wang et al (2014) modified a particle-packing method developed by Brouwers and implemented to design self-compacting concrete. This method was adopted in the study with the objective of reducing paste quantity and enhancing particle packing of concrete systems while maintaining concrete quality and performance. Concrete samples with varying aggregate sizes and supplementary cementitious materials were designed to have a particle distribution modulus, q, with value range of 0.23 to 0.29.

Fresh properties examined include passing ability, flowability, yield stress, formwork pressure, segregation resistance, viscosity and set time. While hardened state properties examined include compressive strength, surface resistance, shrinkage and air structure. Compared to conventional self-compacting concrete, self-compacting concrete designed based on modified Brouwers particle packing method showed good fresh and hardened state performances while consuming 20% less binder content.

Particle packing method mix design incorporated with Two Stage Mixing Approach (TSMA)was implemented to produce recycled aggregate concrete by complete replacement of natural coarse aggregate with recycled aggregates. Results obtained from the evaluation implemented on the prepared concrete samples were compared to those of concrete prepared using IS: 10262 (2009) method of mix design. From the results obtained, the fresh and hardened properties of RAC prepared with particle packing method were better (Pradhan et al, 2017).

Liu et al (2021) carried out an experimental study to validate the implementation of Dewar's particle packing model for recycle concrete aggregates. In the study, aggregates with varying multi-size classes were used. Void ratios of aggregate mixtures were assessed experimentally and compared with the predictions. The study showed that a size ratio adjustment factor would be necessary to calibrate the model for implementing fine RCA while high predicting accuracy for implementing coarse RCA was obtained. A practical method for assessing the axe ratio adjustment factor was proposed. It was also observed that the powder within the investigating aggregates showed limited impact on the estimation of void ratio of aggregate mixtures. However, it has an effect on the final mix design as well as on the fresh and hardened concrete properties.

Implementation of particle packing model mix design by others has been limited to vary small number of aggregate sizes. Hence, it is imperative to evaluate the performance of high strength concrete incorporating more aggregate sizes for the development of high strength concrete.

2. Materials and Methods

The material implemented in the production of high strength concrete in the current study include the conventional limestone-based cement produced by Dangote Cement, five varying size ranges of fine and coarse aggregates, water, superplasticizer and metakaolin implemented as partial substitute for cement. The mixing procedure was implemented based on the optimized aggregate gradation method outlined in the particle packing mix design model.

First, aggregates were subjected to physical tests which include specific gravity tests, bulk density test and sieve analysis. The prepared aggregates are mixed based on the proportions of the computed mix aggregate obtained via the adopted mix design as shown in Table 1 below.

Other tests implemented on the mixed and cured concrete include slump test implemented to assess workability of fresh concrete. Mechanical properties of the prepared concrete were assessed via compression test, tensile test and flexural test. Hardened concrete samples were tested after 7-, 14- and 28-days wet curing.

3. Results and Discussion

A. Workability Result

The workability of the prepared concrete was assessed via slump test. The slump results of the concrete mix are shown in Table 2. The results in Table 2 are plotted and shown in Figure 1. From the plots, it is observed that as the replacement of cement with metakaolin in the concrete mixture increases from 0 to 20, the slump increases. This shows that the workability of the concrete prepared by varying grades of aggregates is improved by the inclusion of metakaolin powder.

Table 2
Slump of fresh concrete mixture

Mix	Percentage Replacement of cement	SLUMP mm
0.25	0	507
	5	564
	10	612
	15	636
	20	655
0.30	0	534
	5	614
	10	659
	15	670
	20	727
0.35	0	585
	5	630
	10	697
	15	761
	20	800
0.40	0	638
	5	696
	10	746
	15	798
	20	852

B. Compressive Strength of Concrete

Concrete samples were cast into cubes and cured for 7, 14 and 28 days. Thereafter, compression tests were performed on the samples and the results obtained are presented in Table 3 as shown. Plots of the results of seven, fourteen and twenty-eight days are equally presented in Figures 2, 3 and 4 showing graphically, the development of compressive strength with the inclusion of metakaolin as partial substitute for cement.

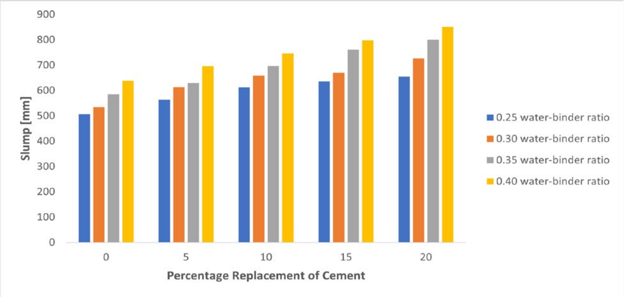

Fig. 1. Plot of slump against replacement levels of cement

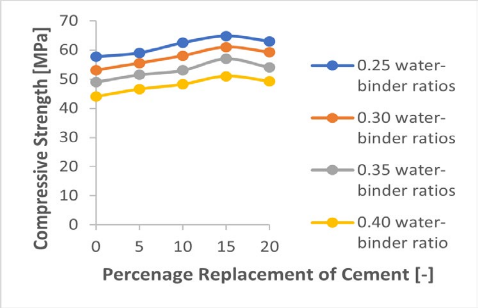

Fig. 2. Seven days compressive strength

Table 1
Mix proportion for mixed concrete

Mis	% Replacement	19.5mm Coarse Aggregate	12.5mm Coarse Aggregate	6.3mm Coarse Aggregate	2.362mm Fine Aggregate	1.18 Fine Aggregate	Cement Content	Metakaolin Content	Superplasticizer
0.25	0	732.08	600.01	432.30	256.71	165.75	362.28	0	4.35
	5	732.08	600.01	432.30	256.71	165.75	344.17	18.11	4.35
	10	732.08	600.01	432.30	256.71	165.75	326.05	36.23	4.35
	15	732.08	600.01	432.30	256.71	165.75	307.94	54.34	4.35
	20	732.08	600.01	432.30	256.71	165.75	289.82	72.46	4.35
0.30	0	732.08	600.01	432.30	256.71	165.75	333.65	0	4
	5	732.08	600.01	432.30	256.71	165.75	316.97	16.68	4
	10	732.08	600.01	432.30	256.71	165.75	300.28	33.37	4
	15	732.08	600.01	432.30	256.71	165.75	283.60	50.05	4
	20	732.08	600.01	432.30	256.71	165.75	266.92	66.73	4
0.35	0	732.08	600.01	432.30	256.71	165.75	309.26	0	3.71
	5	732.08	600.01	432.30	256.71	165.75	293.80	15.46	3.71
	10	732.08	600.01	432.30	256.71	165.75	278.33	30.93	3.71
	15	732.08	600.01	432.30	256.71	165.75	262.87	46.39	3.71
	20	732.08	600.01	432.30	256.71	165.75	247.41	61.85	3.71
0.4	0	732.08	600.01	432.30	256.71	165.75	288.19	0	3.46
	5	732.08	600.01	432.30	256.71	165.75	273.78	14.41	3.46
	10	732.08	600.01	432.30	256.71	165.75	259.37	28.82	3.46
	15	732.08	600.01	432.30	256.71	165.75	244.96	43.23	3.46
	20	732.08	600.01	432.30	256.71	165.75	230.55	57.64	3.46

Table 3
Compressive strength result

Mix	Percentage Replacement of cement	7 days compressive strength	14 days compressive strength	28 days compressive strength
0.25	0	57.67	65	77.67
	5	59	68.3	79.5
	10	62.5	72.47	82
	15	64.83	75.83	83.83
	20	63	73	82.43
0.30	0	53	61	74.3
	5	55.5	64.43	76.27
	10	58	68.6	77.43
	15	61	74	80.37
	20	59.2	72.53	79.03
0.35	0	49	57	69.47
	5	51.5	60.1	71.97
	10	53	64	74.67
	15	57	67.8	77.07
	20	54	64.67	75.23
0.40	0	44	52	64.17
	5	46.55	54.4	66.89
	10	48.2	57	70.33
	15	51	60.83	73.03
	20	49.24	58.67	71

Table 4
Splitting tensile strength result

Mix	Percentage Replacement of cement	7 days Tensile strength	14 days Tensile strength	28 days Tensile strength
0.25	0	2.04	2.16	2.36
	5	2.06	2.22	2.39
	10	2.12	2.28	2.43
	15	2.16	2.34	2.46
	20	2.13	2.29	2.44
0.30	0	1.95	2.1	2.31
	5	2	2.15	2.34
	10	2.04	2.22	2.36
	15	2.1	2.31	2.41
	20	2.06	2.29	2.39
0.35	0	1.88	2.03	2.24
	5	1.93	2.08	2.28
	10	1.95	2.15	2.32
	15	2.03	2.21	2.36
	20	1.97	2.16	2.33
0.40	0	1.78	1.93	2.15
	5	1.83	1.98	2.19
	10	1.86	2.03	2.25
	15	1.92	2.09	2.29
	20	1.88	2.06	2.26

Table 5
Flexural strength result

Mix	Percentage Replacement of cement	7 days flexural strength	14 days flexural strength	28 days flexural strength
0.25	0	5.7	6.05	6.61
	5	5.76	6.2	6.69
	10	5.93	6.38	6.79
	15	6.04	6.53	6.87
	20	5.95	6.41	6.81
0.30	0	5.46	5.86	6.46
	5	5.59	6.02	6.55
	10	5.71	6.21	6.6
	15	5.86	6.45	6.72
	20	5.77	6.39	6.67
0.35	0	5.25	5.66	6.25
	5	5.38	5.81	6.36
	10	5.46	6	6.48
	15	5.66	6.18	6.58
	20	5.51	6.03	6.51
0.40	0	4.97	5.41	6.01
	5	5.12	5.53	6.13
	10	5.21	5.66	6.29
	15	5.36	5.85	6.41
	20	5.26	5.74	6.32

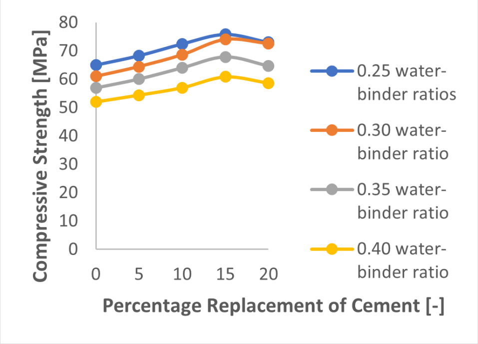

Fig. 3. Fourteen days compressive strength

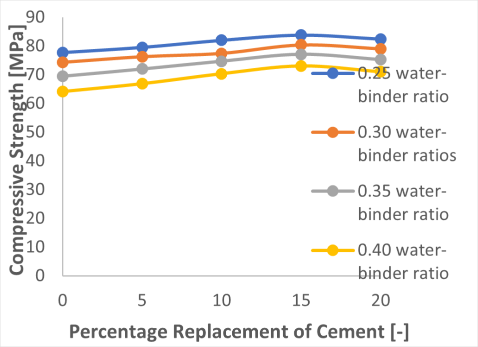

Fig. 4. Twenty-eight days compressive strength

From the table of compressive strength, the compressive strength of the concrete samples follows a consistent trend. The inclusion of metakaolin into the concrete matrix results in the increment of compressive strength. The increment is steady up to 15% inclusion of metakaolin and slightly reduces at 20% level of inclusion. However, compared to the control samples, all the concrete containing metakaolin have better compressive strength. Also, as the curing ages of the concrete samples increases, from seven days to 28 days, at corresponding mix proportions, the compressive strength of concrete increases. The compressive strength reduces with the increment in the water-binder ratios.

The improvement of compressive strength by metakaolin can be attributed to nucleating effect of its small particles which results in the reduction of voids in the concrete matrices and the pozzolanic reaction of metakaolin with other aggregates in the concrete mixture.

C. *Splitting Tensile strength of Concrete*

The fresh concrete cast into cylindrical mold and cured for 7-, 14-, and 28 days of wet curing. The results obtained from the test are presented in Table 4. Also, the results are plotted and the twenty-eight days results are shown in Figure 5.

Similar to the compressive strength results, the partial replacement of cement with metakaolin resulted in the steady increment of its splitting tensile strength up to 15% inclusion of metakaolin which slightly reduces at 20% level of inclusion below the strength at 15%. With respect to the curing ages of the concrete samples, at corresponding water-binder ratios, the tensile strength development demonstrates a positive correlation with the curing age; increases with increase in curing age. However, a negative correlation is observed with the water-binder ratio; reduces as the water-binder ratio increases.

Similar to the compressive strength, the improvement in the splitting tensile strength by the inclusion of metakaolin can be attributed to the nucleating effect of its small particles which results in the reduction of voids in the concrete matrices and the pozzolanic reaction of metakaolin with other aggregates in the concrete mixture.

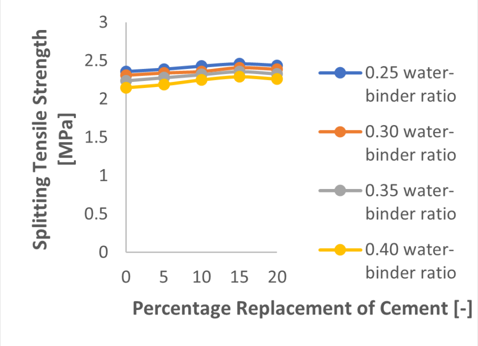

Fig. 5. Twenty-eight days splitting tensile strength

D. *Flexural Strength Result*

Beam samples were subjected to flexural tests and the results obtained are presented in Table 5 shown below. Also, the twenty-eight days strength is plotted against percentage inclusion of metakaolin and shown in Figure 6. The results obtained from Table 4 above similar trend with the compressive strength results shown in Table 3. This shows a strong correlation between compressive strength, tensile strength and flexural strength. The partial replacement of cement with metakaolin resulted in the steady increment of its splitting tensile strength up to 15% inclusion of metakaolin which slightly reduces at 20% level of inclusion below the strength at 15%. As the curing ages of the concrete samples increases, the flexural strength development demonstrates a positive correlation with the curing age; increases with increase in curing age. On the other hand, a negative correlation is observed with the water-binder ratio; reduces as the water-binder ratio increases.

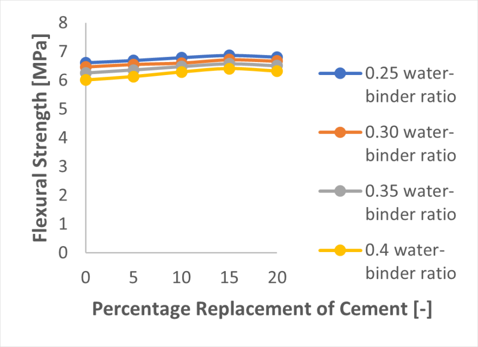

Fig. 6. Twenty-eight days flexural strength

Similar to the compressive strength and splitting tensile strength, the improvement in the flexural strength by the inclusion of metakaolin can be attributed to the nucleating effect of its small particles which results in the reduction of voids in the concrete matrices and the pozzolanic reaction of metakaolin with other aggregates in the concrete mixture.

Therefore, it is observed that the inclusion of metakaolin into the concrete prepared based on optimized mix design as partial substitute for cement up to 20% results in the increment in the flexural performance of the concrete.

The graph (Fig. 3) illustrates the development of compressive strength of control samples and metakaolin based samples across water-binder ratios after seven days curing. From the plots shown above, it is observed that the compressive strength increased as the percentage inclusion of metakaolin increases from zero to fifteen percent. The compressive strength slightly reduced as the percentage inclusion of metakaolin increased to 20%. The maximum compressive strength of the is observed for mix sample of 0.25 water-binder ratio and 15% inclusion of metakaolin with a value of 64.83 MPa.

A similar trend is observed for fourteen days concrete samples as observed in the seven days concrete samples as shown in Fig. 3. The compressive strength of the concrete increased as the content of metakaolin increased. The maximum value is observed for concrete with 0.25 water-binder ratio and 15% inclusion level of metakaolin with a value of 75.83 MPa.

The twenty-eight days compressive strength as in Figure 4 follows similar trend as observed for seven days and fourteen days cured samples. A maximum value of 83.83 MPa at 0.25 water-binder ratio and 15% inclusion of metakaolin.

From the above illustrations, it can be observed that the inclusion of metakaolin into the concrete matrix of optimum aggregate size results in the improvement of compressive strength at all water-binder ratios.

In similar manner, the twenty-eight days splitting tensile strength results and flexural strength results are shown in figures 5 and 6.

The splitting tensile strength as shown Figure 5 shown for twenty-eight days cured samples follows similar trend as observed for seven days and fourteen days cured samples. A maximum value of 2.46 MPa at 0.25 water-binder ratio and 15% inclusion of metakaolin was obtained.

Similar to the compressive strength, the splitting tensile strength has been observed to have increased upon the inclusion of metakaolin as partial substitute for cement in the concrete mixture.

The flexural strength as shown in the plot above for twenty-eight days cured samples follows similar trend as observed for seven days and fourteen days cured samples and is shown in Figure 11. A maximum value of 6.87 MPa at 0.25 water-binder ratio and 15% inclusion of metakaolin was obtained. Similar to the compressive strength and the splitting tensile strength, the flexural strength has been observed to have increased upon the inclusion of metakaolin as partial substitute for cement in the concrete mixture.

4. Conclusion

In this study, an experimental investigation has been implemented to investigate the workability and mechanical properties concrete blended with metakaolin. The concrete samples were produced based on continuous gradation aggregates with an optimized mix design, the particle packing model adopted for the production of concrete samples. Metakaolin was implemented into the concrete mix in partial replacement of cement contents in percentages of 5, 10, 15 and 20.

The following observations were made from the results obtained and the analysis carried out on the results;

i. Physical parameters assessed for the materials showed acceptable range of values for specific gravities and bulk densities which were implemented in the computation of mix proportions for the concrete production.
ii. The workability of the concrete was improved by the introduction of metakaolin into the concrete mix. Slump test carried out on fresh concrete showed that the slump increased upon as the metakaolin content increased.
iii. The adopted mix design resulted in an improved mechanical performance for the high strength concrete. Consistently, the compressive strength, splitting tensile strength and flexural strength were improved by the inclusion of metakaolin. Compared to the control samples, the inclusion of metakaolin increased the mechanical performance.
iv. All mechanical properties assessed showed maximum performance at 15% inclusion of metakaolin across water-binder ratios. At 20% level of inclusion, the strength values dropped slightly below the 15% strength. This indicates optimum level of metakaolin inclusion to be 15%.
v. The improvement of mechanical performance of the concrete were based on the reduction of voids in the concrete mixture. The introduction of metakaolin powder further reduced the void content in the concrete matrices. Hence the increased compression, tensile and flexural performances of the concrete.

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