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Assessment of the influence of Nano-Silica on the behavior of mortar using factorial design of experiments

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HIGHLIGHTS

- Water/cement ratio and Nano-Silica (%) are selected as factors.
- Compressive strength and water absorption of mortar are selected as responses.
- The procedures of 3^2 factorial designs are used for analysis of results.
- Main effects of the selected factors are found to be significant.
- Interactions of factors have no substantial influence on the responses.

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ABSTRACT

The influence of water/cement ratio and addition of Nano-Silica as partial replacement of cement on the compressive strength and water absorption of mortar mixes is a topic of current research. For this purpose, 3^2 factorial design is selected with water/cement ratio and Nano-Silica (%) as factors. The levels of water/cement ratio are kept at 0.40, 0.45 and 0.50. The levels of other factor Nano-Silica (%) is kept at 0%, 1.5%, and 3%. Compressive strength at 3, 7, and 28 days and water absorption at 28 days are selected as responses. The Analysis of Variance (ANOVA) of test results for aforementioned responses considering the factors depict that the selected factors are significantly affecting the test results. However, the analysis indicates that interactions of factors are not statistically significant. In addition to the above, the study illustrates that consistency and setting time of cement paste is considerably affected by the incorporation of Nano-Silica.

1. Introduction

Concrete, most widely used construction material is found to be largely dependent upon the behavior of its constituent phases such as aggregates, cement mortar and aggregate–paste interface. Moreover, a stronger and durable concrete could be achieved by modifying the behavior of cement mortar. Therefore, several investigations have been carried out to improve the behavior of cement mortar and paste [1]. Pozzolanic materials have been added in cement paste and mortar to enhance its mechanical and durability characteristics along with densification of microstructure. Previous investigations demonstrated that the incorporation of fly ash brought significant changes in the behavior of cement paste and mortar along with reduction of consumption of cement quantity [2,3]. In addition to fly ash, silica fume was found to be quite efficient in improving cement paste and mortar characteristics at early days owing to increased rate of cement hydration at early hours. Moreover, strength of mortar and paste enhanced owing to reduction in the quantity of $Ca(OH)_2$(CH) crystals and strengthening of cement paste–aggregate interfacial zone by filling of the minute pores present in it [4–6]. Other materials such as metakaolin and ground granulated blast furnace slag was found to be reasonably capable of upgrading the behavior of cement paste and mortar [7–9]. These materials provided a prospect of reduction of consumption of cement and helped in developing sustainable construction materials.

Currently, new materials of nano-scale size have been invented with highly improved characteristics owing to the rapid progress in Nanotechnology. The nano-materials were found to be quite efficient in modification of the properties of concrete in nano-metric scale. Nano-particles could bring significant modifications in

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the mechanical and micro-structural behavior of cementitious composites owing to reduction of voids present in C–H–S structure and increase in cement hydration acting as nucleation centers [10]. Although nanoparticles have enormous benefits for several applications, various factors such as cost, toxicity of nanoparticles, unavailability of skilled workers and lack of advanced instruments are some factors those hinders their use [11]. Among all the available nano-materials for application in cement and concrete, silica nano-particles preferably called Nano-Silica (NS) was found to be reasonably proficient in achieving significant improvements in the mechanical and micro-structural characteristics of paste and mortar [12]. The addition of NS accelerated the rate of hydration of cement pastes during the early hours of curing because of its high surface and highly reactive nature [13]. Senff et al. [14] investigated the heat of hydration of cement pastes up to 22 h incorporating 0%, 0.65% and 1.3% of weight of cement for a fixed w/b ratio. The outcomes of the study showed that noticeable changes in the reactivity of cement hydration as compared to the control paste during 4–7 h curing. Moreover, addition of NS to cement paste and products caused significant decrease in workability of the mixture on account of the immediate reaction between the NS and the liquid phase of the cementitious mixtures. This could be attributed to the formation of gels having high water retention capacities [15]. Fresh properties of cement pastes and mortars containing NS were investigated and reduction in setting time and workability was reported elsewhere [16,17]. Kuo et al. [18] conducted a similar type of study to investigate flowability of paste by incorporating 0%, 1%, 2% and 3% NS by the weight of cement. The investigation demonstrated about reduction of setting times and flowability with increasing percentages of NS. Kontoleontos et al. [19] reported that significant reduction in the mortar flow with the addition of 4% of colloidal NS in the cement paste made with ultra fine cement. The mortar flow was found to be decreased 0% and 57.14% with the incorporation of 2% and 4% colloidal NS respectively. Moreover, decrease by 6.25% and 12.5% final setting times were reported with the addition of 2% and 4% NS respectively. The addition of 1% NS reduced Initial and final setting time of cement paste 2.68% and 3.54% respectively. Another study reported that initial and final setting time decreased to 2.68% and 3.54% respectively, with the addition of 1% NS into mortar mixes [20]. Kawashima et al. [21] demonstrated that fluidity of fly ash mortars significantly reduced with the addition of NS. However, the fluidity of mortar made with a fixed percentage of NS had higher value for higher FA content.

The addition of NS in cement paste had significant influence on the strength of these cementitious products. However, the conclusion related to use of the percentage of NS for achieving optimum strength was varied, as it was dependent upon factors such as w/b ratio, curing conditions, admixture used and size of nano-particles. The 7 and 28 days Compressive Strength (CS) of paste increased to 29.41% and 72.41% respectively with the incorporation of 3% NS. Moreover, 7 and 28 days flexural strength of mortar made with 3% NS increased to 26.92% and 27.59% respectively [22]. Qing et al. [23] investigated strength of cement paste made with NS at levels of 0%, 1%, 2%, 3% and 5%, by weight of cement. The 28 days CS of paste was found to be 24.75% for a replacement of 5% NS, which could be attributed to the pozzolanic activity of NS. Moreover, addition of NS could able to absorb the crystals of $Ca(OH)_2$ produced from hydration of cement and transformed it to C–S–H. However, another study reported that CS of cement paste reduced when 5% NS added to paste, and 1% NS produced best results in terms of strength [24]. Shih et al. [25] investigated CS of cement paste containing 0%, 0.2%, 0.4%, 0.6% and 0.8% with a fixed *W*/*C* ratio 0.55. The outcome of study illustrated that 0.6% NS produced optimum CS. The CS of cement paste was examined with different types of NS and it was stated that the strength of cement paste improved irrespective of type of NS [26]. The indirect tensile strength of cement paste was significantly increased with the incorporation of 2% NS [27]. Thuadaij and Nuntiya [28] stated that cement paste modified with 10% NS produced optimum strength at a fixed *W*/*C* ratio. The strength of cement paste was affected by the curing temperature and strength was found to be more when specimens were cured under high temperature [29].

Several investigations have been carried out to study the influence of NS on the strength of cement mortars. Li et al. [30] demonstrated that cement mortar made with 10% NS at w/b ratio 0.5 had produced optimum strength. Flexural strength of mortar specimens increased with increasing percentages of NS and optimum strength was achieved at a level of 5% NS [31]. Jo et al. [32] found that CS increased with increasing percentages of NS and mortar mix with 12% NS produced optimum strength. Development of CS from 3 to 28 days of mortar containing 0%, 3% and 10% NS was investigated and it was concluded that mortar made with 10% NS produced the highest strength among all the designed mixes [33]. Sadrmomtazi et al. [34] examined the CS of mortar mixes made with 0%, 1%, 3%, 5%, 7%, and 9%, of NS at a fixed w/b ratio of 0.5. The results showed an increasing trend with the increasing level of NS and reached an optimum strength at 7%. The compressive and flexural strength of mortars containing polypropylene fibers and colloidal NS improved with the increasing percentages of NS [35]. The CS of mortar made with a varying *W*/*C* ratio and percentages of NS was investigated and 3.5% of NS were found to be optimum level. Arefi et al. [36] demonstrated that compressive and tensile strength of mortar highest at 3% NS when *W*/*C* ratio was 0.4. The CS of mortar made with ultrafine cement incorporating NS was investigated and the optimum level of NS was fixed at 4% [19]. It was observed that the CS of fly ash/sludge mortar improved significantly with the addition of 3% NS [37]. Other studies in the field of application of NS in the mortar mix confirmed about considerable improvements in strength and microstructure with the addition of NS [38–42].

Determination of the optimum quantity of materials for mixes depending upon several factors and having subjected to many performance constraints are often complex and prolonged. This complexity could be made simple with the utilization of procedures of statistical experimental design and analysis, as the properties of the final product are dependent upon the relative proportions of the components of the mixture rather than their absolute amounts. Moreover, well designed mixture experiments are reasonably effective in identifying the best combination of factors for the achievement of optimized properties of the mixture. Among all the available methods of Design of Experiments (DOE), one method, popularly known as the Factorial design, in which the $\boldsymbol{q}$ mixture components are reduced to $\boldsymbol{q - 1}$ independent factors by taking the ratio of two-components. The significance of each component and model development for concrete could be carried out by ANOVA. ANOVA was found to be one of the proficient tools that allow the simultaneous study of the effects of all the parameters by carrying out the single analysis [43]. Alqadi et al. [44] implemented a factorial design for analysis of CS of self-compacting concrete with consideration factors such as cement content, water to powder ratio, fly ash content, and superplasticiser. The outcome of this study indicated that optimum CS could be achieved when the factors cement content, water to powder ratio, fly ash contents were at a high level and the dosage of superplasticiser was at low level. Furthermore, the influence of several factors on the behavior of cement mortar and paste could be easily studied using factorial design plans [17].

The critical observations from the existing literatures in the area of applications of NS in cement paste and mortar are summarized as follows: