Journal of Cleaner Production 83 (2014) 273–285

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Statistical techniques to analyze properties of nano-engineered concrete using Recycled Coarse Aggregates

Bibhuti Bhusan Mukharjee*, Sudhirkumar V. Barai

*Department of Civil Engineering, Indian Institute of Technology Kharagpur, India*

ARTICLE INFO

*Article history:*
Received 31 January 2014
Received in revised form
17 July 2014
Accepted 18 July 2014
Available online 29 July 2014

*Keywords:*
Colloidal nano-silica
Compressive strength
Design of experiments
Modulus of elasticity

ABSTRACT

This paper aims at evaluating effect of incorporation of Nano-Silica as replacement of cement on natural and recycled aggregate concrete using Two-way Analysis of Variance (ANOVA). In this study 3, 7 and 28 d compressive strength, Modulus of Elasticity, Water Absorption, Density, and Volume of voids are considered as responses. Principles of general factorial design is adopted for selection of number of mixes with consideration of Nano-Silica (%) and Recycled Coarse Aggregate (%) as two factors for this study. The ANOVA of test results depicts that these two factors have significant effect on compressive strength, Water Absorption, Density, and Volume of voids. However, the analysis of results indicates that only Recycled Coarse Aggregate (%) has considerable influence on Modulus of Elasticity. Moreover, there are no substantial influences of interaction of two factors on the selected properties of concrete.



## 1. Introduction

Globally, construction and demolition activities are considered primarily to be responsible for generating a major fraction of the millions of tons of yearly solid demolition waste. Management of such gigantic amount of construction and demolition waste are causing sever environment problems due to unavailability of sufficient number of landfills and increase in cost of waste treatment (Blengini and Garbarino, 2010). Moreover, enormous use of natural resources for extracting aggregates for production of aggregates results sharp lessening of these sources. Therefore, several countries all over the world have tried to find alternate sources of aggregates to fulfill this growing demand of raw materials for construction activities (Gencel et al., 2012). Several instances were found about the application of these waste materials after recycling and it was proven to be beneficial for human civilization (Medina et al., 2013). Concrete recycling was seriously taken by Australia and Japan and rate of recycling were very high in these countries (Tam, 2009). Moreover, the waste concrete that forms a major portion of this waste was separated and was crushed to produce recycled aggregates. However, fine fractions of the recycled aggregates should not be used for replacement of natural sand due to adverse effects on workability, only the use of coarse recycled aggregates were recommended (Buyle-Bodin and Hadjieva-Zaharieva, 2002).

Previous researchers extensively documented the uses of Recycled Coarse Aggregates (RCA) as partial or full replacement of Natural Coarse Aggregates (NCA). The incorporation of RCA up to 30% had no significant effect on the compressive strength (CS) of concrete. However, the reduction of CS of concrete containing 100% RCA was up to 25% as compared to control concrete (Ajdukiewicz and Kliszczewicz, 2002). Tensile strength, elastic modulus and other mechanical properties were found to be affected with the partial or full replacement of virgin aggregates (Yang et al., 2008). Barbudo et al. (2013) demonstrated that the replacement of 100% natural aggregates was feasible without affecting the major mechanical properties, with the proper use of water-reducing admixtures. The durability characteristics such as resistance to freezing thawing, shrinkage, and sulfate ion penetration of Recycled Aggregate Concrete (RAC) were drastically reduced with the use of recycled aggregates (Li, 2008). The carbonation depth and chloride penetration of RAC was similar or slightly increased as compared to that of Natural Aggregate Concrete (NAC) (Otsuki et al., 2003). Moreover, the frost resistance of concrete was also affected with the use of RCA in concrete mixes (Zaharieva et al., 2004). However, with careful selection of the replacement percentages of aggregates and treatments prior to batching, concrete produced with RAC had durability similar to that NAC (Richardson et al., 2011).

Several methods were proposed in literature for improvement of properties of recycled aggregates as well as RAC. The qualities of

* Corresponding author. Tel.: +91 8900164774.
*E-mail addresses:* bibhuti.2222@gmail.com, 10ce90r15@iitkgp.ac.in (B.B. Mukharjee).

http://dx.doi.org/10.1016/j.jclepro.2014.07.045
0959-6526/

**Table 1**
Properties of colloidal Nano-Silica.

| Specific gravity | Particle size | pH value | Solid content | Colour | $SiO_2$ content |
|---|---|---|---|---|---|
| 1.12 | 8–20 nm | 10.11 | 39% | White | 99.1% |

RCA could be improved by adopting ultrasonic cleaning techniques or impregnation with a solution of silica fume (Katz, 2003). Significant improvement in the properties of RCA could be achieved by soaking them with various acids prior to the use in concrete owing to the reduction in the amount of adhered mortar (Tam et al., 2007). Two stage mixing approach was developed with modification of normal mixing method for upgrading of mechanical and durability properties of RAC (Tam and Tam, 2008). Kong et al. (2010) developed a novel triple mixing method utilizing the various pozzalanic materials such as fly ash and fine grounded blast furnace slag to achieve additional improvement in properties of RAC. It was reported that concrete mixes containing 50% replacement of cement with blast furnace slag produced significant improvement in terms of strength of concrete (Berndt, 2009). Moreover, addition of various pozzolanic materials such as silica fume, fly ash and blast furnace slag had produced significant enhancement in characteristics of RAC (Li et al., 2009).

Currently, with the significant development of nano-technology, novel nano-materials could be produced by modification of materials behavior at nano-scale. Application of these nano-products have been growing popularity for modification of behavior of civil engineering materials due to its capability to produce substantial up gradation of cement based products (Pacheco-Torgal, 2013). Nano-Silica (NS) was quite efficient in improving mechanical, durability and Microstructural behavior cement paste during early days as compared to the silica fume (Qing et al., 2007). The properties of mortar were enhanced with the incorporation of NS in mortar mixes (Senff et al., 2010). Moreover, another study revealed about the use of various percentages of colloidal NS in mortar mixes to improve its CS (Mukharjee and Barai, 2014). Improvement in properties of concrete with the incorporation of colloidal NS was reported (Said et al., 2012). The influence of incorporation of colloidal NS on behavior of 100% RAC was investigated and the study illustrated that CS of RAC mixes could be compared with that of NAC with addition of three percentages of NS (Hosseini et al., 2011).

Design of Experiments (DOE) is a useful tool for understanding the process and process variable, when a process or product depends upon several factors. Procedures of DOE could be implemented for study of influencing factors on the different properties of concrete. Moreover, statistically designed mixture experiments are quite useful in identifying the best combination of factors for achievement of optimized properties of concrete mixture. Factorial design, one of the several experimental designs available, in which ‘q’ mixture components are reduced to q-1 independent factors by taking ratio of two components and the significance of each component and model for concrete could be determined using Analysis of Variance (ANOVA). The advantages of using ANOVA technique is that it allows the simultaneous study of the effect of all the parameters by carrying out this single analysis. Sneff et al. (2012) utilized factorial design to study the individual as well as interactive effect of nano-$SiO_2$ and $TiO_2$ on the rheology and at long-term properties of the hardened mortars. The study concluded that the contribution of individual as well as interactive effects of factors defined by factorial designs did not lead to a significant effect on the CS as those were observed in the case of rheology. Nehdi and Summer (2002) adopted $3^2$ experimental plan for study the influence of silica fume, fly ash and ground granulated blast furnace slag content on setting time, drying shrinkage, sulfate expansion and CS of mortar. The outcomes of the study illustrated that a good quality high-fineness ground granulated blast furnace slag could be utilized for replacement levels of cement up to 60% without any major shortcomings in the mortar behavior. López-Gayarre et al. (2009) adopted factorial designs for analysis of density, absorption, compressive strength, elastic modulus, amount of occluded air, penetration of water under pressure and splitting tensile strength of recycled aggregate concrete. The quality of the recycled aggregate (amount of declassified and source of aggregate), the percentage of replacement on the targeted quality of the concrete to be produced (strength and workability), the granular structure of concrete and replacement criteria were selected as factors for this analysis. ANOVA technique was used for this study and it was found that the factors declassified content, base concrete, objective workability, reference sieve curves, and replacement criteria are not significant out of all selected factors. Moreover, the study concluded that the factors like quality of recycled aggregates and the percentage of replacement substantially influenced the most properties of RAC.

Several studies have been carried out to investigate the influence of incorporation of RCA on mechanical and durability behavior of concrete mixes. Moreover, effects of application of NS as a replacement of cement on behavior of cement-based products have been extensively studied. However, research works comprising of application NS in concrete with RCA rarely found in literature. Therefore, influence of RCA(%) and NS(%) on parameters of concrete such as compressive strength, elastic modulus, water absorption, density and volume of voids is investigated in this study using general factorial design. The experimental results of study are analyzed using ANOVA and contour plots, main effect and interaction plots have been utilized to express the analysis of results.

## 2. Experimental programme

Experimental investigation have been carried out to examine the behavior of concrete produced by substituting the whole of the natural coarse aggregates with recycled coarse ones retrieved from the concrete demolition waste. Nano-Silica is added as partial replacement of in cement both natural and recycled concrete mixes and its influence was studied.

### 2.1. Materials

Ordinary Portland Cement (OPC) of 43 Grade, having consistency 32% and specific gravity 3.12, fulfilling the requirements of Bureau of Indian Standard Specifications (IS 8112, 1959) was

**Table 2**
Properties of Aggregates.

| Type of aggregate | Bulk density ($kg/m^3$) | | Apparent specific gravity | Specific gravity | Impact value (%) | Los Angeles abrasion value (%) | Crushing value (%) |
|---|---|---|---|---|---|---|---|
| | Loose | Compact | | | | | |
| NFA | 1525 | 1698 | 2.66 | 2.62 | – | – | – |
| NCA | 1504 | 1654 | 2.81 | 2.72 | 15.35 | 19.72 | 15.11 |
| RCA | 1321 | 1418 | 2.67 | 2.46 | 34.85 | 36.56 | 31.52 |