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Hybrid fiber reinforced self compacting concrete with fly ash and colloidal nano silica: A systematic study

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HIGHLIGHTS

- Systematic study of producing HyFRC using different binders and fibers.
- Fly ash, nano silica, crimped steel fiber and polypropylene fiber are used with four levels each.
- Optimization of HyFRC mix is conducted using L16 Taguchi Orthogonal Array.
- Application of multiple linear regression analysis to predict the tensile strengths.
- A good correlation exists between tested and predicted values.

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ABSTRACT

The current systematic study investigates properties of hybrid fiber reinforced self compacting concrete (HyFRSCC) with crimped steel fibers (CSF) and polypropylene fibers (PPF) along with class F fly ash (FA) and colloidal nano silica (CNS). Optimization of HyFRC mix is conducted using L_{16} Taguchi Orthogonal Array where additive has four levels. Combination of 10% FA, 0.4% CNS, 1.25% CSF and 0.167% PPF found to be optimal recommendation. Multiple linear regression analysis predicts equations of tensile strength as the function of cylinder compressive strength, for combination of FA, CNS, CSF and PPF. A good correlation between tested and predicted values is obtained.

1. Introduction

Cement mortar and concrete are commonly used materials in the infrastructure development across the world due to their adaptability, easy availability of raw materials at low cost. For the construction of multi storied high rise earthquake resistance structures, prestressed concrete bridges and heavy industrial foundations, there is a need of high strength concrete. But, it was very difficult to possess consistent quality of high strength ordinary concrete by using vibration. So, there was a need of producing high performance concrete with uniform quality, better volume stability, much higher strength and durability [1,2]. Aiming at uniformity and full compaction of concrete without vibration, in 1980 s the researchers in Japan had developed a new type of concrete called Self Compacting Concrete (SCC). SCC is a concrete with high workability, more cohesive and uniformity properties which can be flown, filled in and compacted by gravity only through the congested reinforcement areas without any sign of segregation and bleeding [3,4].

Across the globe, cement production is one of the sources of emission of CO_2 [5,6]. Hence, it is required to add suitable binder to cement concrete which emits less CO_2 without affecting strength and durability [5]. Fly ash is a waste material of burnt coal produced in a thermal power plant. During early ages of hydration, the pozzolanic reaction of FA is at slow rate and increases with age. IRC: SP:62-2004 specifies that, fly ash can be used as a partial replacement of cement (OPC) up to an extent of 35% [7]. Among all available nano particles, nano silica (NS) can be efficiently used in cement mortar and concrete in accelerating the hydration process during early stage and filling the voids of Calcium-Silicate-Hydrates. Due to its high specific surface area and ultra-fine particle size, a small amount of NS can result in

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more rate of hydration with enhanced particle packing [8–10]. NS is available in two forms: dry powder and colloidal liquid suspension. Liquid form of NS is preferred to powder form in concrete, as the former is more dispersive in water and has reduced segregation as compared to the dry form [8]. Chithra et al. had conducted experimental investigations on the effect of CNS on workability, mechanical and durability properties of HPC with copper slag as partial fine aggregates [11]. It was observed that, incorporation of up to an optimum content of 2% CNS in mortar and concrete has increased the strength gain at early ages due to its high specific surface area and high pozzolanic activity. But, beyond 2%, as the quantity of CNS is more than quantity of liberated lime, the pozzolanic activity get reduced resulting in decrease in compressive strength. Addition of CNS could compensate the slow rate of hydration of FA on the hydration of cement [12].

The presence of fibers in concrete can make it more ductile than normal concrete and offer resistance to cracks. Fiber reinforced concrete (FRC) does not break after the onset of the first crack like normal ordinary concrete [4,13]. Effect of fibers mainly depends on its type, shape and size, tensile property of the fiber, volume fraction and the properties of the matrix. Fibers suitable for reinforcing concrete may be of steel, glass, polyethylene, polypropylene, polyvinyl alcohol, polyester, aramid and natural fibers [2]. Steel fiber (SF) is widely used due to its affinity with concrete, the ease of use, high toughness and resistance to static and dynamic loads. The addition of SF has a relatively small effect on precracking compressive strength and elastic modulus but has a significant effect on the post cracking behaviour [14]. Mixing of CSF up to 2% by volume of concrete may increase the tensile resistance of concrete [15]. Randomly distributed steel fibers provide bridging effects across the micro-cracks and thus prevents them to grow further [4,16]. Long fibers show a better post peak failure pattern than that of short fibers [17]. PPF are smooth monofilaments with low density, chemically inert and have non-corrosive properties which can be used as reinforcement in concrete. The short PPF can effectively bridge the micro cracks as they are very thin and their number is more in concrete than that of long steel fibers for the same fiber volume [18]. The fibers when used in hybrid form can result in enhanced flexural toughness as compared to a singly fiber reinforced concrete [18]. In hybrid fiber system, short fibers may resist development of micro cracks and long fibers can more efficiently prevent the development of macro cracks [5]. The fibers bridge microcracks in concrete with FA and nano particles and develop bonding force between the concrete and the randomly oriented SF [19]. A maximum of 2% volume content of fibers with FA and NS is appropriate [2]. As per the experimental study of Khaloo et al., addition of 2% steel fibers by volume reduced the workability of SCC as the more fiber volume could not pass easily through the rebar, causing the failure of passing ability of SCC [4]. Xu et al. had studied on the effect of fiber-matrix interfacial transition zone (ITZ) on the mechanical performance of hybrid steel-polypropylene fiber reinforced concrete and found that, thickness of fiber-matrix ITZ mainly depends on type of fibers used in concrete [20]. Mobini et al. had studied that, pyrogenic NS200 with lower surface area was more effective than NS300 in achieving more strength at different levels of SF and PPF [16]. Tabatabaeian et al. had studied the effects of hybrid steel and polypropylene fibers on the rheological, mechanical and durability properties of high strength SCC [21]. Xu et al. had observed strength characteristics of SFRC which depends mainly on concrete grades, concrete types, curing time, fiber geometry, aspect ratio and volume fraction [22]. Yap et al. had conducted laboratory tests to find out the flexural toughness characteristics of steel-polypropylene hybrid fibers using oil palm shell aggregates and observed that, the mixes with 0.9% steel and 0.1% PP hybrid fibers had shown the highest improvement in toughness index and the residual strength factor [23]. In hybrid fiber system, the stiffer steel fibers improve the first crack stress and the ultimate strength; while the flexible and ductile PP fibers lead to improve ductility and post-cracking toughness [23,24]. From the micro structural study of El-Dieb, an improved ductility was observed due to the very strong bond between fibers and cement paste. Hence, the fibers provide toughening mechanism in concrete due to fiber pull out mechanism which do not exist in control mix without any fiber [25].

During 1950 s in Japan, Genichi Taguchi had developed a process optimization technique. Orthogonal array approach is used to study a lot of variables with limited number of experiments [26]. But, the conclusions from those small scale experiments are valid over the entire experimental domain with the available control factors.

1.1. Research significance

In the current systematic study, an attempt is made to use class F FA, CNS, CSF and PPF to prepare HyFRSCC, which has not been explored so far as per the authors' knowledge. The aim is to study the fresh and hardened properties of M_{60} grade of HyFRSCC with a constant water binder ratio of 0.38 and using polycarboxylate ether based superplasticizer of 0.2% by weight of binder. Each of the additives is called as factor. Each factor has four levels of addition. 5%, 10%, 15% and 20% of FA and 0.1%, 0.2%, 0.3% and 0.4% of CNS by weight of cement replacement were used. 0.5%, 0.75%, 1.0% and 1.25% of CSF and 0.042%, 0.084%, 0.125% and 0.167% of PPF by volume of concrete were used. Both crimped SF and PPF are added to increase the inherent tensile strength property of hardened concrete. To ascertain the fresh properties of SCC, the maximum total amount of fiber content is restricted to 1.42% by volume of concrete. L_{16} orthogonal array of Taguchi method is followed to avoid the conduct of huge amount of experiments. The number of mixes have been reduced from 4^5 (1024) to only 16, leading to overall advantages in terms of economy and time. Only 16 mix combinations along with one control mix without any additive have been considered to predict the behaviour of HyFRSCC.

2. Material characterization

2.1. Materials

The materials used in concrete in this study include Ordinary Portland cement (OPC) of 53 grade, fly ash, colloidal nano silica, crimped steel fiber, polypropylene fiber, coarse aggregate with 16 mm maximum size, river sand as fine aggregate, superplasticizer and potable water.

2.1.1. Cement

All the concrete mixes were prepared by using Ordinary Portland cement (OPC) of 53 grade confirming to the requirements of Bureau of Indian Standard Specifications (IS:12269–2013) [27]. The specific gravity of cement was 3.15. The consistency and fineness modulus of cement was 30% and 322.5 m^2/kg respectively. The average 28d compressive strength of cement mortar was found to be 61.70 MPa.

2.1.2. Class F fly ash (FA)

Class F FA with specific gravity of 2.19 and fineness of 114.30 m^2/kg satisfying the requirements of ASTM C 618 – 15 [28] was collected from nearby Kolaghat thermal power plant, West Bengal, India. The chemical compositions of OPC and FA are shown in Table 1.

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