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Development of sustainable concrete using recycled coarse aggregate and ground granulated blast furnace slag

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HIGHLIGHTS

- Strength of concrete decreases with increase in RCA/GGBFS/RCA & GGBFS contents.
- Less reduction in tensile strength is observed with the use of RCA and GGBFS.
- Use of GGBFS shows superior performance in RAC as compared to NAC.
- Concrete mix with 50% RCA and 40% GGBFS achieves the desired mechanical properties.

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ABSTRACT

The present investigation aims to use recycled coarse aggregate (RCA) and ground granulated blast furnace slag (GGBFS) as replacement of natural coarse aggregate (NCA) and ordinary Portland cement (OPC) for developing sustainable concrete. Sixteen numbers of concrete mixes are prepared with 0%, 25%, 50% and 100% replacement of NCA by RCA for each 0%, 20%, 40% and 60% replacement of cement by GGBFS. The effects of RCA and GGBFS on fresh and hardened concrete properties such as workability, compressive strength, split tensile strength, flexural strength, rebound number, density, water absorption and volume of voids are experimentally investigated. The test results obtained in the present investigation show that the workability increases with the use of RCA or GGBFS or both of these two. The compressive, split tensile and flexural strength decrease with increase in the percentages of RCA or GGBFS or both. The reduction in split tensile and flexural strength of the concrete mixes containing RCA or GGBFS or both RCA and GGBFS is less pronounced unlike its compressive strength. The values of rebound number obtained from non destructive test (NDT) show the similar trend with the results of compressive strength. Water absorption and volume of voids of the concrete mixes increases with increase in RCA content. However, the use of GGBFS improves the quality of the concrete mixes by improving the ITZ and bond between mortar and RCA. The concrete mix with 50% RCA and 40% GGBFS achieves values of these properties closer to those of the concrete mix without RCA and GGBFS. Finally, the concrete mix with 50% RCA and 40% GGBFS is considered as the optimum mix which is satisfying the target mean strength of the mix design and producing sustainable concrete by saving 40% of cement and 50% of NCA and utilizing maximum waste products such as GGBFS and RCA.

1. Introduction

Nowadays, concrete is an important material in the construction industries due to its significant contribution towards accelerated civilization. However, with the advancement in industrialization and urbanization, most of the developed regions suffer from major environmental problems like depletion of natural resources and sustainable waste management [1,2]. Moreover, activities like rehabilitations, reconstruction and destruction of existing concrete structures produce large amount of construction and demolition (C & D) waste every year. To minimize the various environmental problems, many countries have been using the C & D waste as an alternative to the construction materials like natural fine and coarse aggregates (NFA and NCA) for making concrete. Aggregates prepared through screening, crushing and sieving of waste pieces of concrete is often called recycled coarse aggregates (RCA). Although the use of RCA as an alternative to NCA reduces the energy consumption and environment pollution, but the attached mortar of RCA make its physical and mechanical

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character inferior to that of NCA [3]. Previous review works reflect a number of studies related to the use of RCA in the concrete [4–8]. The two important factors related to RCA that influences the behaviour of recycled aggregate concrete (RAC) are content of RCA in the concrete and the strength of parent concrete from which the RCA have been obtained. Most of the previous studies observed no significant reduction in compressive strength of concrete when NCA is replaced up to 30% by RCA in making RAC [7,9–15]. However, compressive, split tensile and flexural strength of concrete with replacement of different percentages of NCA even up to 100% with RCA are reduced up to 30%, 10% and 23%, respectively in comparison to the normal aggregate concrete (NAC) [9,16–20]. Moreover, the reduction in elastic modulus is more pronounced (even up to 45%) than the other mechanical properties due to poor performance of RCA and weak transition between old and new mortar [8,21]. It has been also observed that water absorption of RCA is considerably higher than the NCA [9,14,22–24] which negatively affects the mechanical and durability of RAC as the substitution level of RCA increases in the concrete. Properties like drying shrinkage and creep coefficients also vary directly with variation in the content of RCA [21,25].

Similarly, many industrial by-products such as fly ash, GGBFS, metakaolin, silica fume and rice husk ash have been used as mineral admixtures for improvement in the properties of concrete. Among the available mineral admixtures, GGBFS has been potentially used in concrete as a replacement of cement [26–34] because of its latent hydraulic property which enhances the long term compressive strength and sometimes raises the early and later age flexural strength of concrete. Moreover, the use of GGBFS also improves the workability [35] and durability properties of concrete [31,36,37].

The previous studies reflect the poor mechanical and durability aspects of RAC in comparison to NAC. Therefore, to mitigate the deficiencies, different techniques have been proposed in the literature to enhance the RCA quality and the performance of RAC, such as treatment of adhered mortar of the RCA [38,39], strengthening of adhered mortar of RCA [40–45], two stage mixing approach [46,47] and use of mineral admixtures such as metakaolin, silica fume, fly ash, GGBFS and micronized biomass silica as replacements of cement [48–53]. Moreover, use of GGBFS in RAC improved the chloride penetration resistance and other durability properties of RAC [48,52].

As discussed above, limited research works were conducted to study the mechanical and durability properties of concrete using RCA and GGBFS [48,52,53]. Kou et al. [48] studied the properties, such as compressive strength, split tensile strength, ultrasonic pulse velocity (UPV), drying shrinkage and chloride penetration, of concrete using only two types of concrete mixes, i.e. concrete mix with 50% RCA and 55% GGBFS and 100% RCA and 55% GGBFS. Ann et al. [52] also investigated the compressive strength, split tensile strength, permeability and corrosion resistance of concrete made with 100% RCA and 65% GGBFS only. Cakir [53] considered the concrete mixes with 25%, 50%, 75% and 100% RCA for only two different percentages of 30% and 60% of GGBFS in order to study the properties like compressive strength, split tensile strength, density and water absorption. Since, the physical, chemical and mechanical properties of RCA and GGBFS have a wide range of variations depending upon their sources and hence, it is very difficult to reach a final conclusion with the above limited research. Moreover, flexural strength, non destructive test (NDT) parameter, such as rebound hammer, and other durability properties are yet to be addressed. This needs further extensive research on concrete using RCA and GGBFS available as waste products at different locations. Therefore, the present work aims to have a systematic study for assessing the influence of locally available RCA and GGBFS on various properties of concrete as mentioned above including flexural strength and NDT characteristics for potential use of these materials in the field applications.

2. Experimental program

2.1. Materials

2.1.1. Binders

The binding materials used in this investigation were 43 grade Ordinary Portland cement in an agreement to IS: 8112 [54] and GGBFS collected from Jindal Steel and Power Limited, Angul, India. Standard tests have been conducted in laboratory for determination of various physical and mechanical properties of the binders as per BIS specifications [55–59] and those results are furnished in Table 1. From Table 1, it is found that the Blaine surface area of GGBFS (5000 cm^2/g) is higher than that of OPC (3200 cm^2/g) which implies GGBFS is finer than that of OPC. Fineness of GGBFS is a major factor influencing the reactivity of GGBFS and early strength development of concrete [60]. It is reported by Swamy [26] that an increase in fineness of GGBFS to 2–3 times that of OPC benefits on engineering properties of concrete, such as setting time, bleeding, heat of evolution and durability. In order to obtain satisfactory performance the surface of GGBFS may be in the range of 4000–6000 cm^2/g [61]. The surface area of the presently used GGBFS is within the range.

The scanning electron microscopy (SEM) analysis of GGBFS was done and presented in Fig. 1. It is seen that the GGBFS consists of particles of random sizes and geometry and also the surface of the particles are relatively smooth. It is due to the interimpacting and interrubbing of granulated blast furnace slag between the steel balls in the ball mill.

The X- ray diffraction (XRD) analysis of cement and GGBFS was also made and results were shown in Figs. 2 and 3, respectively. The results of XRD of cement (Fig. 2) show that the chemical compounds present in OPC are in crystalline form, which are visible by a number of sharp peaks. It is seen that the calcium silicate (Alite and Belite) is the main chemical constituents of OPC, which are mainly responsible for strength development. Similar type of XRD of OPC is also reported in the literature [19]. In addition to calcium silicate, the presence of tri calcium aluminate (C_3A) and gypsum ($CaSiO_4 \cdot 2H_2O$) are also observed in the XRD of OPC. Fig. 3 shows the XRD of GGBFS in which the XRD peaks are hardly identified. In addition, a wide diffusive hump between the angles 23° and 35° is also observed in the diffractogram of GGBFS. The above facts indicate that the GGBFS is mostly having amorphous character. However, small traces of gehlenite (mililite), merwinite and diopside, which are the major mineral composition of GGBFS, are identified. Apart from that the traces of calcite, wollastonite and quartz, which are minor components of GGBFS, are also observed.

The chemical properties of the binders were obtained from the test and furnished in Table 2. From the chemical properties of the binders (Table 2), it is seen that in GGBFS, the lime (CaO) content

Table 1
Physical and mechanical properties of binders.

Properties	Test method	OPC	GGBFS
Specific gravity	IS: 4031(Part-11) [55]	3.11	2.82
Fineness (cm^2/g)	IS: 4031(Part-2) [56]	3200	5000
Consistency (%)	IS: 4031(Part-4) [57]	32	–
Setting times	IS: 4031(Part-5) [58]		
Initial setting time (min)		140	–
Final setting time (min)		300	–
Mortar strength (MPa),	IS: 4031(Part-6) [59]		
3 days		29.96	–
7 days		35.20	–
28 days		46.02	–