**Ferrocrete - Flexural Strength Analysis**

**3.2 Flexural Strength**

The compressive strengths and the reaction product quantification in iron carbonate binder systems have already been reported in detail [12,31]. Here, the flexural strengths of plain and fiber-reinforced iron-based binder systems are reported along with their comparison to OPC systems. Figure 5 shows the flexural strengths of plain and fiber-reinforced iron carbonate binders after 6 days of carbonation and the corresponding OPC pastes after 28-days of hydration for comparison. The results presented here suggest that the iron carbonate binder is about four-to-six times stronger than the traditional OPC paste in flexure. This can be attributed to a combination of the stronger carbonate matrix along with the presence of unreacted iron particles in the microstructure as shown in Figure 4. Both the binders are observed to exhibit increases in flexural strength with inclusion of fibers, with the iron-based system showing a much pronounced increase. While it has been proved that addition of glass fiber in OPC system results in increase in toughness with only minor increase in flexural strength [32–34], the iron-based binder shows a different trend where the flexural strength is increased significantly with the incorporation of glass fibers into the matrix. An enhancement in flexural strength of about 50% is observed for the iron-based binder when 0.5% glass fibers by volume is incorporated, but further fiber addition does not appear to correspondingly enhance the material behavior. Such an observation is noticed for the Mode I fracture toughness of these binder systems also, and the explanation is provided in a later section.



Figure 5: Comparison of flexural strength of 6-day carbonated iron Carbonate sample and OPC paste after 28 days for different fiber dosage

**3.3 Fracture of Notched Beams and Fracture Parameters**

In this paper, the fracture parameters of the iron-based and OPC binder systems are studied using the TPFM. TPFM idealizes the pre-peak non-linear behavior in a notched specimen through an effective elastic crack approach. The beam sizes and the notch depth are same for both the systems, thereby rendering the comparisons of the fracture parameters free of size effects. The effect of fiber volume fractions on the fracture parameters are also evaluated in conjunction with the response of the matrix phase.

**3.3.1 Cyclic Load-CMOD response of notched beams**

The representative load-CMOD responses are shown in Figure 6 for the iron-based binder and the companion OPC-based binder with and without fiber reinforcement. Figure 6(a) plots the load-CMOD response for the control OPC and iron-based binder (without fiber reinforcement), which clearly depicts the fundamental differences in the flexural response of these matrices. The significantly higher peak load and improved post peak response of the iron-based binder as compared to control OPC binder can be attributed to the presence of unreacted metallic iron particles (Figure 4) which are inherently strong and ductile. It needs to be noted that the iron-based binder contains higher amounts of larger pores (average size > 0.2 µm) even though the total pore volumes are comparable [31], and consequently, demonstrates compressive strength that is slightly lower than that of the OPC binder [12]. However, the presence of strong and ductile phases in the microstructure dominates the flexural response, as shown earlier. The incorporation of fibers in an OPC matrix makes it ductile as observed from the post-peak response and the larger CMODs for the fiber reinforced systems as opposed to the unreinforced materials shown in Figures 6(b) and (c); a response that is well documented. Both the peak load and the residual load are significantly higher for the iron carbonate binder, with and without fiber reinforcement, depicted in Figures 7(a) and (b). The incorporation of glass fibers enhances the peak load of the iron-based binder much more than it does to the OPC binder, signifying the synergistic impact of the iron carbonate matrix (including the unreacted iron particles) and fiber on the flexural response. The residual load for the control binders were measured at a CMOD value of 0.12 mm whereas a CMOD value of 0.25 mm was chosen for the binders with fiber reinforcement. The residual loads provide an indication of the crack-tolerance and the post-peak response of these systems.



Figure 6: Representative Load-CMOD responses for iron carbonate binder and comparison with OPC paste for (a) Control; (b) 0.5% and (c) 1.0% fiber volume fraction



Figure 7: (a) Peak load, and (b) residual load of OPC and iron carbonate binders as a function of fiber volume fraction

**3.3.2 KICSand CTODc of iron carbonate composite systems and their comparison to OPC-based systems**

Figure 8 reports the two major fracture parameters-fracture toughness (KICS) and critical crack tip opening displacement (CTODC) derived using TPFM for both the binders, as a function of the fiber volume fraction. Figure 8(a) shows that the fracture toughness values of the iron-based binders are much higher than those of the control OPC binders (~ 5-7 times) irrespective of the fiber volume fraction. An increase in fiber volume fraction is found to enhance the toughness of both the binder systems, as expected, attributed to the crack-bridging effects of the fiber and the resultant increase in energy dissipation under load. The K­ICSvalues of the iron carbonate binder range from 30 MPa.mm0.5 to 50 MPa.mm0.5, which is approximately half of those of glass ceramics [35], polycrystalline cubic zirconia, SiN, Alumina [36] and high-performance structural ceramics such as SiC [37], and five times larger than the companion OPC binder. It is noteworthy to state that the above-mentioned ceramics are prepared via high-temperature processing whereas the iron-based binder in this study is processed at ambient temperature and pressure in a CO2 environment. In the unreinforced OPC matrix, the only mechanism of strain energy dissipation is crack extension. The significantly higher KICSof the iron-based binder, even for the unreinforced case, as compared to the OPC binder could be attributed to the crack bridging and/or deflection effects of the ductile, unreacted metallic iron particles in the matrix, many of them which are elongated as can be observed from the micrographs in Figure 4. The strong reinforcing phase (the unreacted metallic particles) imposes a closing pressure on the crack thereby bridging the cracks and the elastic incompatibility and debonding between the metallic particle-carbonate matrix interfaces contributes to crack deflection. The influence of the unreacted iron particles in improving the crack resistance and toughness is augmented by the toughening mechanisms due to the incorporation of fibers, as can be noticed from Figure 8(a). Beyond a certain volume fraction of fibers, further toughness enhancement is negligible for the iron-based binders because the distribution of the unreacted iron particles and the fibers in the matrix is expected to be sufficient for crack bridging/deflection. However, as expected, an increase in fiber volume fraction, in the ranges reported in this paper, enhances the toughness of the OPC-based binder system, the reasons for which are well documented [38–43].



Figure 8: (a) Fracture toughness, and (b) critical crack tip opening displacements of iron carbonate and OPC-based binders

The critical crack tip opening displacements (CTODC), which indicates the limit beyond which unstable crack propagation begins is shown in Figure 8(b) as a function of the fiber volume fraction for both the binders. A rather uniform increase in CTODc with fiber volume fraction is observed for both the binders. The unstable crack propagation threshold limit (CTODC) for the unreinforced iron-based control binder is found to be about three times higher as compared to that of the corresponding OPC paste, also attributable to the reasons described earlier. The difference in CTODC between the two binder types reduce to a certain extent as fibers are incorporated. The KIC and CTODC values of the two binders indicate that the iron-based binder yields significantly improved crack resistance and ductility than the conventional OPC systems due to the presence of unreacted metallic iron powder surrounded by a carbonate matrix [12,31].

The KIC-CTODC relationships of the two binders are compared in Figure 9(a), where an increase in the fracture toughness is observed with an increase in the critical opening size of the crack. While the increase in KICS is proportional to an increase in CTODc for the OPC binders, for the iron-based binder, the increase in KICS is not prominent beyond a certain CTODc value (or fiber volume fraction, since CTODc-fiber volume fraction relationships are linear for both the binder systems as shown in Figure 8(b)). The reason for this observation was provided earlier. The critical crack length (ac) values obtained from TPFM are shown in Figure 9(b), as a function of the fiber volume fraction. The critical crack length increases with increase in fiber volume for both the binders as expected. In unreinforced binders, the iron-based system has a higher critical crack length owing to the contribution from elongated, elastic iron particles. However, at a higher fiber volume fraction, the critical crack lengths for both the binders are comparable even though KICS and CTODc are higher for the iron-based binder. This shows that, in the iron-based systems, beyond a certain fiber volume fraction, enhancement in fracture properties are negligible for reasons explained earlier (even though the performance is much better than the corresponding OPC systems). This aspect is investigated in further detail through the use of resistance curves in the following section.



Figure 9: (a) Fracture toughness-critical crack tip opening displacement relationship; (b) Variation in critical crack length with change in fiber dosage for iron carbonate binder and OPC