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# Effect of metallic aggregate on strength and fracture properties of HPC

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**Abstract**

In order to make clear the effect of metallic aggregate on strength and fracture properties of high-performance concrete (HPC), two control concretes made of conventional coarse aggregate with minimum compressive strength of about 60 and 80 MPa, and three concretes with 25%, 50% and 75% of conventional aggregate replaced by metallic coarse aggregate for each control concrete were fabricated and studied in laboratory, respectively. Compressive strength, splitting tensile strength and complete load–deflection curve of these materials were measured. Additionally, a quantitative roughness analysis of the fracture surfaces was conducted to characterize the fracture surface's roughness. The results show that compressive strength, splitting tensile strength and fracture energy increase as the metallic aggregate replacement volume increases. An explanation based on analysis of the fracture surface is proposed for the metallic aggregate's toughening effect on HPC. 

*Keywords:* Metallic aggregate; Mechanical properties; Fracture toughness; Surface area; High-performance concrete

## 1. Introduction

Concrete may be considered as a kind of three-phase composite material with the three phrases being hardened cement paste, aggregate and interfacial zone between the hardened cement paste and aggregate. From the point of view of composite, the strength is mainly determined by the properties of the weakest phase of a composite. In low- or middle-strength concrete, it has been confirmed by numerous research results that normal weight aggregate is the strongest phase. Failures always happen within the hardened cement paste and/or along the interfacial zone. Therefore, there is no need to pay attention to aggregate's strength (or elastic modules) in the common mix design procedures regarding the strength of concrete. Rather, it is believed that the strength of hardened cement paste is the limiting factor of the strength of concrete. This is the basis of Abrams water–cement ratio law for mix proportioning of concrete. However, for high-performance concrete (HPC), which has generally lower water–binder ratio and higher strength, the strength of the hardened cement paste is often higher than that of aggregate, the cement–aggregate bond strength has been also greatly improved. The possibility of cement paste and interfacial zone failure is relatively lower in HPC than that in the low or medium strength concretes. Consequently, the influence of type and grading of aggregate on the mechanical properties of concrete becomes more important in HPC [1–3]. F.P. Zhou et al. [4] concluded that the difference of strength for the concretes made of different aggregates could be as high as about 40 MPa for the same water–binder ratio of 0.25.

Light metallic aggregates are physically stronger and more resistant against wearing and impact than the conventional aggregates. The investigation by A.F. Oluokun and S.J. Malak [5] showed that the incorporation of ilmenite and hematite coarse aggregates into concrete mixes appeared to significantly increase the compressive strength, enhance the stress–strain behavior, and result in the production of tougher and more ductile concrete with a compressive strength of about 36 MPa.

The research work reported here examined the effect of metallic aggregates on the mechanic properties and brittleness of concretes with compressive strength higher than 60 MPa and water–binder ratio lower than 0.30. Two control mix proportions of conventional coarse aggregate made concrete with a minimum compressive strength of

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Table 1
Chemical composition of hematite aggregate

| Composition | $Fe_2O_3$ | P | S | Cu | $Al_2O_3$ | $SiO_2+Al_2O_3$ | $H_2O$ |
|---|---|---|---|---|---|---|---|
| Percentage | 64.36 | 0.053 | 0.011 | 0.002 | 1.51 | 4.28 | 3.77 |

about 60 and 80 MPa were designed. For each control mix proportion, several mixes with 25%, 50% and 75% of conventional aggregate replaced by metallic coarse aggregate were proportioned. The compressive strength, splitting tensile strength and complete load–deflection curve were measured. Additionally, a quantitative roughness analysis of the fracture surfaces was conducted to determine the surface roughness number $R_s$. The results show that compressive strength, splitting tensile strength and fracture energy increase as the metallic aggregate replacement volume increases. An explanation based on analysis of the fracture surface is proposed for the observed metallic aggregate's toughening effect on HPC.

## 2. Experimental procedures

### 2.1. Raw materials

Cement: The ordinary Portland cement corresponding to ASTM Type I cement was used in all mixture proportions.
Ultrafine slag powder: Slag powder with a Blaine specific surface area of 600 $m^2$/kg was used.
Aggregates: River sand with a fineness modulus of 2.85 was used as the fine aggregate. Crushed stone with maximum size of 20 mm and crush index of 8.3% was used as coarse aggregate.
Metallic aggregate: Hematite aggregate of Australia was filtered to have the same grading curve as conventional aggregate. The chemical composition is listed in Table 1.

### 2.2. Mix proportion

The control mix proportions with a minimum compressive strength of about 60 and 80 MPa are shown in Table 2. In addition, for each control mix proportion, several mixes with 25%, 50% and 75% of conventional aggregate replaced by metallic coarse aggregate were proportioned, named by HPC-$X$–$Y$ ($X$ and $Y$ refer to water–binder ratio and volume percent of metallic aggregate, respectively). The specimen weight increase of HPC-30–25, HPC-30–50 and HPC-30–75 was 4.88%, 9.77% and 13.2%, respectively. The counterpart of HPC-26 series was 4.7%, 9.4% and 14%, respectively. When the replacement ratio of conventional coarse aggregate by metallic coarse aggregate was below 50%, the weight increase was minor.

### 2.3. Casting, curing and testing of specimens

For each mixture proportion, six cubes of $100 \times 100 \times 100$ mm were cast for the measurement of compressive and splitting tensile strength. Three beams of $100 \times 100 \times 515$ mm were cast for the measurement of fracture energy. The specimens were demoulded 1 day after casting, and cured in the room with temperature of $2 \pm 2$°C and relative humidity of 90% for 27 days.

## 3. Experimental results and discussion

### 3.1. Compressive and splitting tensile strengths

From the test data reported in Table 3, appreciable increase in the 28-day strength caused by the incorporation of metallic aggregate can be easily found. The higher the replacement ratio, the higher the compressive strength of concrete. In Fig. 1, the 28-day normalized compressive strength of HPC-30 and HPC-26 series is plotted against the volume ratio of metallic aggregate. The increase of compressive strength for HPC-30 series exceeds that of HPC-26 for the same replacement ratio. The average increase in compressive strength of HPC-30 series varies from about 11.2% for 25% replacement ratio to about 22.1% for 75% replacement ratio. While the counterpart of HPC-26 varies from about 2.31% for 25% replacement ratio to about 4.97% for 75% replacement ratio. Fig. 2 shows 28-day normalized splitting tensile strength of HPC with different metallic aggregate replacement ratios. Increase of splitting tensile strength varies from about 12.4% to 19.1% for HPC-26 series with aggregate replacement ratio from 25% to 75%. For HPC-30 series with metallic aggregate, increase in tensile strength varies from 11.9% to 13.6% for aggregate replacement ratio from 25% to 75%. The increase of HPC-26 series was greater than that of HPC-30 series for splitting tensile strength.

From the results above, it is found that for the HPC-26 series, the increase of splitting tensile strength exceeds that of compressive strength, so the ratio of tensile strength to compressive strength increases from 0.071 for 0% replace-

Table 2
Mix proportions of control concretes

| Series | Cement (kg/$m^3$) | Slag (kg/$m^3$) | Gravel (kg/$m^3$) | Sand (kg/$m^3$) | W/B | Superplasticizer (kg/$m^3$) |
|---|---|---|---|---|---|---|
| HPC-30–00 | 420 | 180 | 986 | 657 | 0.30 | 6 |
| HPC-26–00 | 472 | 202 | 948 | 632 | 0.26 | 6 |

Table 3
Average test results

| Series | Compressive strength (MPa) | Splitting tensile strength (MPa) | Fracture energy (N/m) | Roughness |
|---|---|---|---|---|
| HPC-30–00 | 66.1 | 5.03 | 111 | 1.3219 |
| HPC-30–25 | 73.4 | 5.55 | 159.8 | 1.3342 |
| HPC-30–50 | 79.5 | 5.67 | 190.4 | 1.3699 |
| HPC-30–75 | 80.6 | 5.71 | | |
| HPC-26–00 | 86.5 | 6.15 | 146.28 | 1.3114 |
| HPC-26–25 | 88.5 | 6.91 | 173.22 | 1.3185 |
| HPC-26–50 | 89.8 | 7.29 | 179.44 | 1.3253 |
| HPC-26–75 | 90.8 | 7.32 | | |

ment volume to 0.081 for 75% replacement volume. However, for the HPC-30 series the ratio of tensile strength to compressive strength is almost the same in spite of the content of metallic aggregates.

### 3.2. Fracture energy

Fracture energy of material is defined as the consumed energy divided by newly generated fracture surface area. According to the recommendation of RILEM, three-point bending test on notched beam should be used to determine the fracture energy of concrete. As shown in Table 3, fracture energy increases with the increase of metallic aggregate content for both HPC-30 and HPC-26 series.

The typical load–deflection curves are plotted in Fig. 3. Looking at the ascending branch of the curves, it can be found that the deflection of concrete beam containing metallic aggregate is lower than that of concrete without metallic aggregate at any load level. The lower deflection indicates higher flexural stiffness of concrete beam containing metallic aggregate compared to that of conventional aggregate made concrete beam. The postpeak branch of load–deflection curves of concrete beam containing metallic aggregate is conspicuously less steeped compared

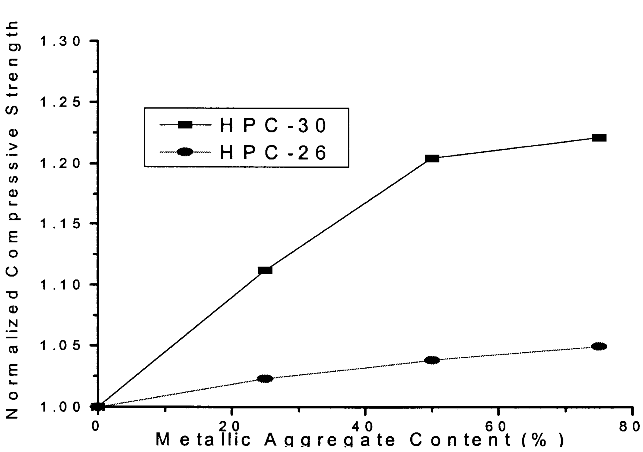


Fig. 1. Normalized compressive strength vs. metallic aggregate content at 28 days.

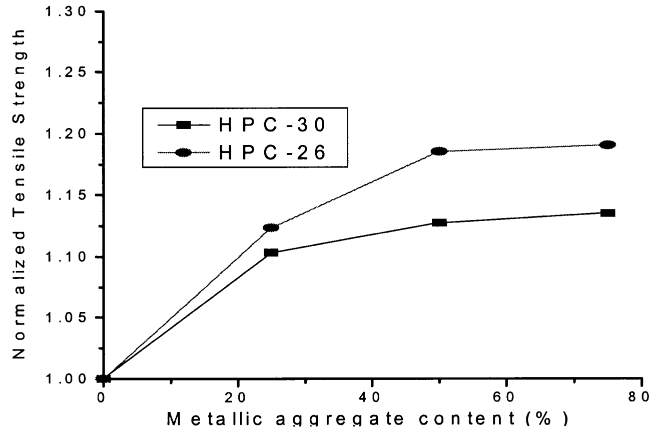


Fig. 2. Normalized splitting tensile strength vs. metallic aggregate content at 28 days.

with that of conventional aggregate made concrete beam. Fig. 4 shows that with the increase of volume replacement percentage of metallic aggregate, the fracture energy increases for both HPC-26 and HPC-30 series. However, the increase of fracture energy of HPC-30 series exceeds that of HPC-26 series at the same volume replacement percentage of metallic aggregate. The average increase of fracture energy for HPC-30 series varies from 43.9% for 25% coarse aggregate replacement to about 71.5% for 50% coarse aggregate replacement. The counterpart for HPC-26 series varies from 18.4% for 25% coarse aggregate replacement to 22.7% for 50% coarse aggregate replacement. It is concluded that metallic aggregate has a desirable toughening effect on HPC, so that the problem of high brittleness of HPC can be overcome to some degree by incorporation of metallic aggregate.

### 3.3. Fracture surface analysis of toughening mechanism

Due to the limitations of previous experimental methods, the fracture surface was often simplified as 2D planes

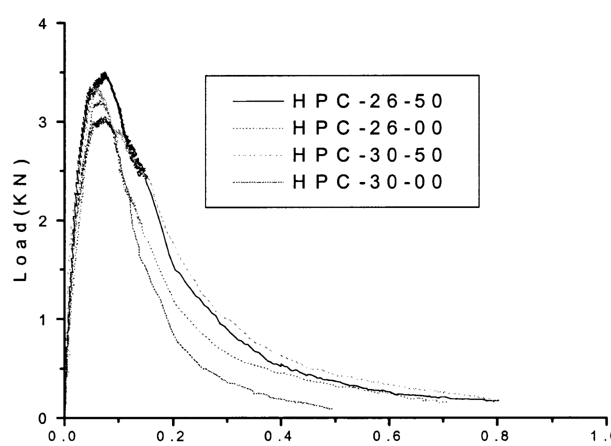


Fig. 3. Flexural load vs. deflection at 28 days.

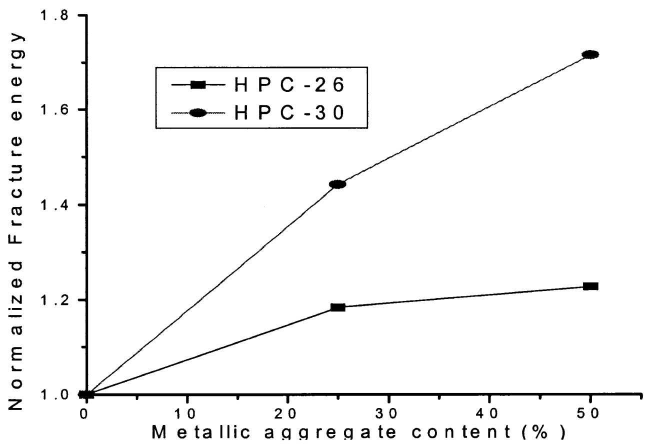


Fig. 4. Fracture energy vs. metallic aggregate content at 28 days.

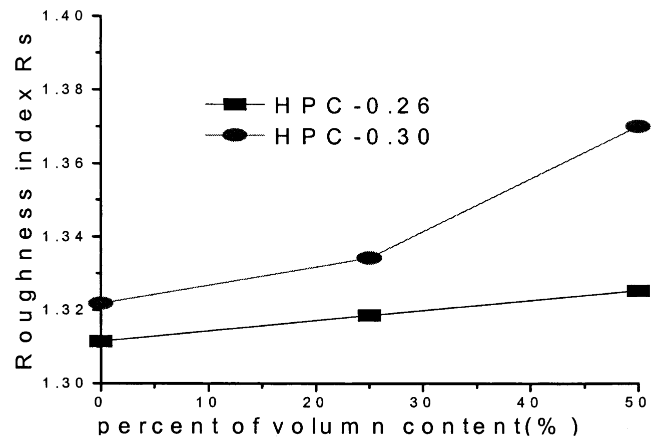


Fig. 6. Roughness index vs. metallic aggregate content.

in the fracture mechanics research of quasibrittle materials such as concrete. This simplification often caused large measurement error, which may impair validity of experimental data of fracture parameters and even may result in wrong conclusions. Furthermore, much valuable information about the micro- and mesostructure and failure mechanisms hiding in the fracture surfaces of materials would be ignored by this simplification.

The fracture surface of notched specimens after three-point bending test could be measured by a new experimental technique based on laser triangulation. The fracture surface was acquired through a CCD camera and frame grabber card and reconstructed in the computer. For more detailed information about experimental technique, please refer to Refs. [6,7]. The reconstructed digitized fracture surface can be used to calculate the roughness of

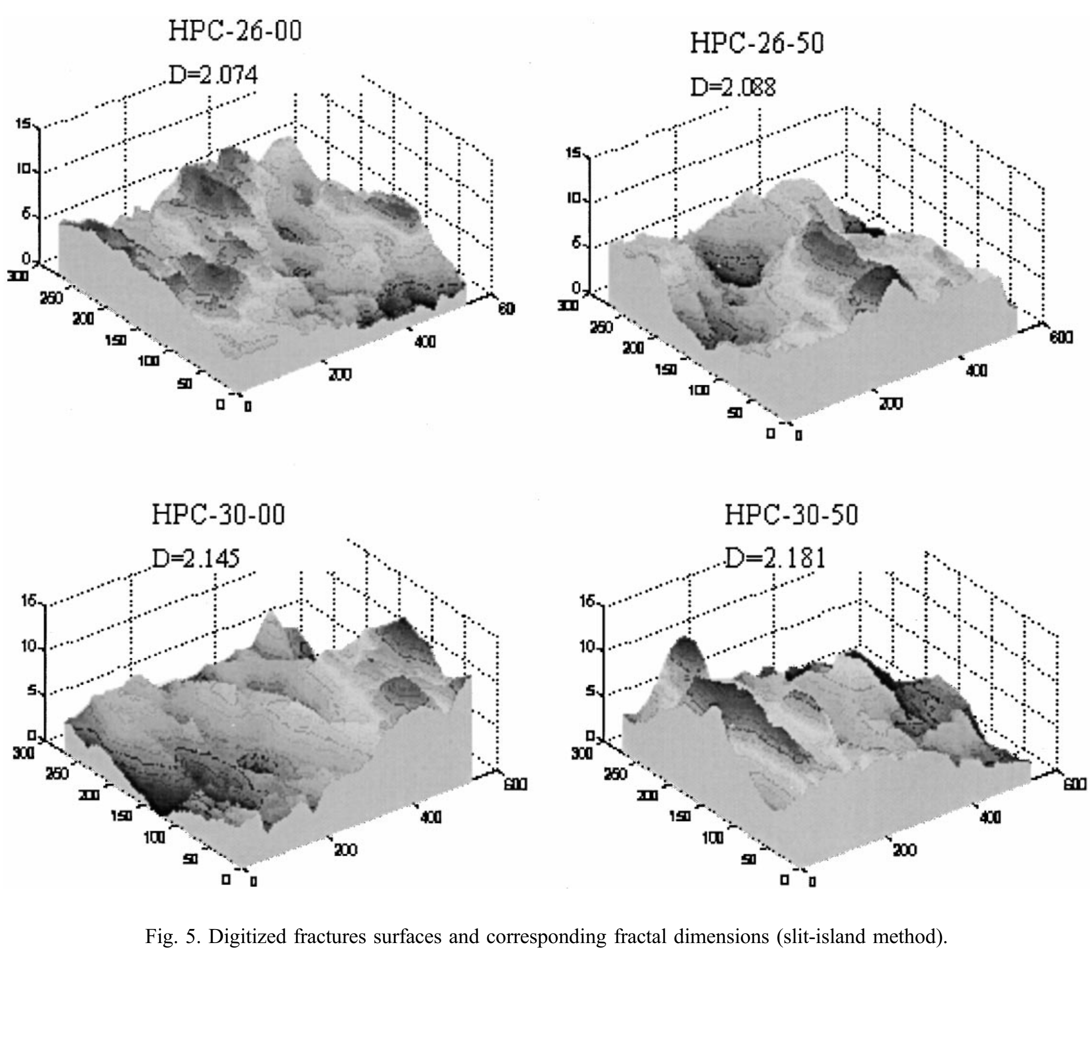


Fig. 5. Digitized fractures surfaces and corresponding fractal dimensions (slit-island method).

the surface $R_s$, which was defined as the ratio of actual surface area $A_a$ to the projected surface area $A_p$ by D.A. Lange et al. [8]. The digitized fracture surface is composed of a large number of tiny units enclosed by the nearest four points in the surface that we call microunits. For each microunit, $R_s$ is the reciprocal of cosine of angle between the actual plane and the projected plane, $1/\cos\alpha_i$. The $R_s$ of the whole surface is the mean value of the $R_s$ of the total microunits. The value of $R_s$ will increase for digitized surface obtained at higher magnification, since new details of the fracture surface can be revealed at higher magnification.

Fig. 5 shows the digitized fracture surfaces for four kinds of mix proportions, and calculated results of fractal dimension are also given in this figure. It is obvious that the fracture surface of HPC-30 series containing metallic aggregate is more irregular than that of the conventional aggregate concrete. The fractal dimension calculated with slit-island method is a parameter to characterize the roughness of fracture surface [9]. The result shows that fractal dimension of HPC-30 is larger than that of HPC-26 series. Due to the metallic aggregate replacement, fractal dimension of both HPC-30 and HPC-26 series increases and the enhanced value for HPC-30 series exceeds that of HPC-26 series. Comparing fractured surfaces of each concretes showed that rupture probability of coarse aggregate is strongly reduced with the replacement of metallic aggregate and the characteristics of the fracture surface is modified. Our past research shows that the rupture probability of coarse aggregate depends on the properties of coarse aggregate [10].

Fig. 6 illustrates the variation of roughness index vs. the metallic aggregate replacement. It is obvious that the roughness index for both HPC-30 and HPC-26 series increases with the metallic aggregate replacement, and the enhanced value of HPC-30 series is higher than that of HPC-26 series.

The result of fracture surface analysis conforms to the result of fracture energy described in the foregoing section. It is easy to understand their relation. When the roughness index or fractal dimension of fracture surface increases or decreases, the actual area need to be created on the fracture surface during fracture also increases or decreases, which means that more or less, energy is consumed in the fracture process at the same specific surface energy rate. Traditionally, instead of actual area of the fracture surface, its projected area, which remains constant in spite of change of the roughness of the surface, is used to calculate the fracture energy of concrete. Therefore, the resulted fracture energy will change with the roughness of the surface, i.e. roughness index or fractal dimensions. In fact, it increases with the roughness of the surface. Test results shown in Fig. 7 agree well with this analysis.

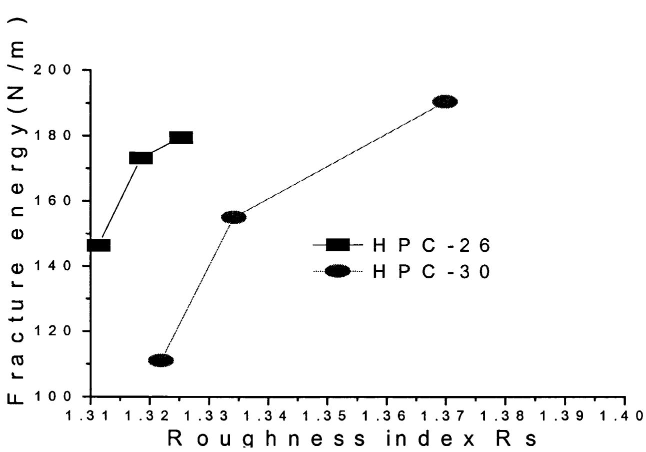


Fig. 7. Fracture energy vs. roughness index.

## 4. Conclusions

The influence of metallic aggregate on the mechanical properties of HPC has been studied in this research work. The following conclusions can be drawn.

(1) The incorporation of metallic aggregate into HCP significantly increased the compressive strength and splitting tensile strength. The maximum increase in compressive strength was 22.1%; in splitting tensile strength was 19.1%.

(2) The incorporation of metallic aggregate into HCP resulted in rougher fracture surface and more ductile behavior. The roughness index of fracture surface for both HPC-30 and HPC-26 series and the toughening effect on HPC increased with the content of metallic aggregate replacement of metallic aggregate. The increase of fracture energy reached 71.5% for materials in this study.

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