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Effect of processing of tail section of tested curve on fracture energy of dam concrete

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ABSTRACT: The design and safety evaluation of dam all require to study the fracture properties of dam concrete intensively and systematically. The fracture energy G_F of dam concrete and wet-screened concrete were investigated in this paper based on our test data of 21 wedge-splitting specimens for 7 groups .
Based on the principle of work-of-fracture, the G_F were calculated by the tested P-CMOD curve. The tested original curves showed that the measured maximum CMOD of some specimens exceeded capacity of the displacement sensor due to employing large size and large size aggregates dam concrete specimens. It led to CMOD value at the tail section curve of some specimens distorted. The tail section of the tested P-CMOD curve need to be fitted, so that the complete P-CMOD curve for calculating fracture energy can be got.
Even so, the complete P-CMOD curves of some wedge-splitting specimens can be tested perfectly. The rationality of fitting the tail section of tested P-CMOD curve by power function or exponential function was studied by contrasting between the tested complete P-CMOD curve and the P-CMOD curve whose tail is fitted. The following three methods were employed to calculate the fracture energy GF of dam concrete and wet-screened concrete: ①Calculated the GF by the tested P-CMOD curve for each companion specimens, then average the results and got the GF of each specimen group. ② Calculated the GF by the averaged P-CMOD curve of which the tail section was fitted by exponential function. ③ Calculated the GF by the averaged P-CMOD curve of which the tail section was fitted by power function.
It was found that the GF calculated by the method ② was the nearest to that calculated by the originally tested complete P-CMOD curve. So the GF of dam concrete and wet-screened concrete were identified by the method ②.
The size effect of fracture energy of dam concrete and wet-screened concrete, and the relationship of fracture energy between dam concrete and wet-screened concrete were discussed preliminarily.

1 INTRODUCTION

The fracture energy of dam concrete is a very important property which can characterize fracture of dam concrete. The coarse aggregate size of dam concrete is 80mm in this paper. The wet-screened procedure is to remove all aggregate particles large than 40mm from the fresh dam concrete. Wet-screened concrete specimens are widely adopted to carry out experiments to evaluate the physical and mechanical properties of dam concrete. This is an approximate method.

The wedge-splitting tests were performed on the specimens which the mix were designed for an actual dam built in China to experimentally investigate the fracture energy of dam concrete and wet-screened concrete. The 12 specimens were divided into 3 groups with different specimen sizes for dam concrete, and another 16 specimens were divided into 4 groups for wet-screened concrete. The details of experiments see our research report (Zhao 2004, Zhou et al. 2004).

Based on the principle of work-of-fracture (RILEM 1985), the fracture energy G_F of dam concrete and wet-screened concrete were calculated by the tested P-CMOD curve. It was shown that the stable tested P-CMOD curves of dam concrete and wet-screened concrete can be obtained by employing the testing method in this paper. However, the measured maximum value of CMOD of some specimens exceeded capacity of the displacement sensor which is 5mm due to employing large size and large aggregate dam concrete specimens in the fracture test. It led to CMOD values of the tail section of the tested P-CMOD curves of some specimens distorted. The tail section of the tested P-CMOD curve need to be fitted, so that the complete P-CMOD curve can be got for calculating the G_F of wedge-splitting specimen.

2 DETERMINATION OF FRACTURE ENERGY OF DAM CONCRETE AND WET-SCREENED CONCRETE BY WEDGE-SPLITTING TEST

The test data come from our research report (Zhao 2004, Zhou et al. 2004), including 3 different sizes wedge-splitting dam concrete specimens and 4 sizes wet-screened concrete specimens. The geometry of specimen is shown in Figure 1 and sizes are shown in Table 1.

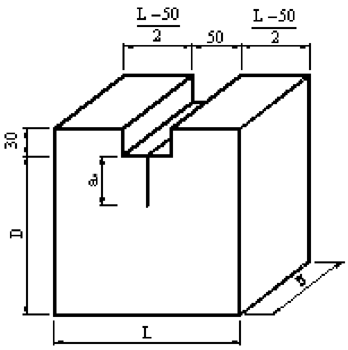


Figure 1. Geometry of wedge-splitting specimen (unit:mm).

Table 1. Sizes of wedge-splitting specimens.

Specimen	Maximum aggregate size (mm)	Sizes of specimens (mm)			
		B	D	L	a_0
WS-d-1			450	450	225
WS-d-2	80	250	800	800	400
WS-d-3			1000	1000	500
WS-w-1			300	300	150
WS-w-2	40	200	600	600	300
WS-w-3			800	800	400
WS-w-4			1000	1000	500

There were 4 companion specimens in each specimen group. By wedge-splitting test, the P-CMOD curve of 3 companion specimens for each group can be tested successfully.

2.1 *Processing of Tail Section of Tested P-CMOD Curve for Wedge-splitting Specimen*

Take a specimen as an example to explain how to obtain a complete P-CMOD curve by processing tail section of the tested curve, then to determine the G_F of dam concrete and wet-screened concrete.

Some specimens may have the almost complete tested P-CMOD curves by wedge-splitting test. For example the specimen WS-1 (see Fig. 2 (a)), the load of tail section of the tested P-CMOD curve reaches to P=80N, compared with the peak load Pmax=4594.8N. It can be considered that the load value closes to zero. The rationality of fitting the tail section of the tested curve by power function or exponential function was investigated by contrasting between tail section of completely tested P-CMOD curve and that of the fitted curve.

In order to got the area enclosed by a complete P-CMOD curve, fitting tail section of the tested curve is needed. According to reference (Xu S.L. et al. 2007), the part after inflection point of descending part of the tested P-CMOD curve(about at the 1/3 of peak load of tail section) was fitted by by power function and exponential function.

In wedge-splitting test, P_v is the vertical load and CMOD is the crack opening displacement.

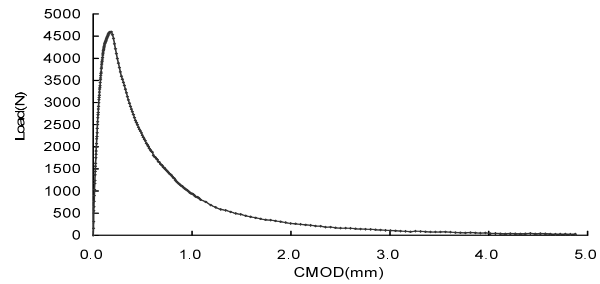
The fitting formula by power function is:

$$P_v = \beta(CMOD)^{-\lambda} \qquad (\beta, \lambda > 0) \tag{1}$$

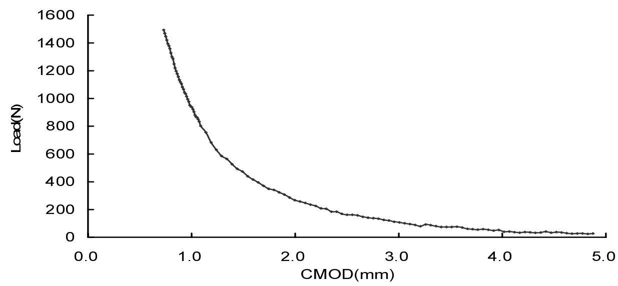
The fitting formula by exponential function is:

$$P_v = me^{-n(CMOD)} \tag{2}$$

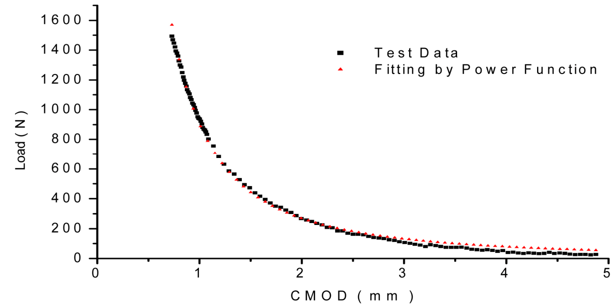
The fitting process of the tail section of tested P-CMOD curve by power function is as follows: The tested P-CMOD curve is shown in Figure 2 (a). The



(a) A tested P-CMOD curve



(b) The segment of the tested curve to be fitted



(c) Comparison between the fitting curve and the tested curve

Figure 2. Fitting tail section of the P-CMOD curve by power function.

part of tested curve from inflection point to tail section which need to be fitted is shown in Figure 2(b). Fitted the curve by formula (1) whose correlation coefficient is R^2=0.9981, the fitting result is shown in Figure 2 (c). The Figure 2 shows that the fitting tail section is a good agreement with the corresponding tested curve. The fitting tail section curve by power function descends slowly than the corresponding tested curve.

The fitting process of tail section of the tested curve by exponential function of wedge-splitting specimen is just like by power function, but with the formula (2) in curve fitting, the fitting result is shown in Figure 3. The area enclosed by the fitting tail section curve by exponential function is some less than that by the tested curve and the fitting tail section curve descends rapidly than the corresponding tested curve.

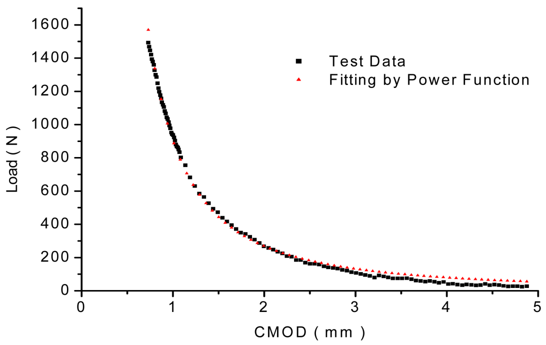


Figure 3. Comparison between the fitting tail section curve by exponential function and the corresponding tested curve.

2.2 *Calculation of Fracture Energy of Dam Concrete and Wet-screened Concrete of Wedge-Splitting Specimen*

A P-CMOD curve is an important tested curve obtained by wedge-splitting test. For each of 3 companion specimens tested in a specimen group, the original test data of the P-CMOD curve reached up to tens of thousands rows to hundreds of thousands rows. The original test data were processed by the procedure such as filtering the test data scattered far from the P-CMOD curve, etc. Then the P-CMOD curve of 3 companion specimens for each group were averaged based on crack propagation process of concrete materials. Thus a representative P-CMOD curve (or called averaged P-CMOD curve) which can characterize the fracture characteristics of the companion specimens can be obtained (Zhao Z.F. et al. 2009).

The following three methods were employed to calculate the fracture energy G_F of dam concrete and wet-screened concrete: ① Based on the principle of work-of-fracture, calculated the G_F by the tested P-CMOD curve for each companion specimens, then averaged the results and got the G_F of each specimen group. ② Calculated the G_F by the averaged P-CMOD curve of which the tail section was fitted by the power function. ③ Calculated the G_F by the averaged P-CMOD curve of which the tail section was fitted by the exponential function. Then compare the different G_F. The G_F obtained by wedge-splitting test can be calculated as follows:

$$G_F=W_0/A_0 \tag{3}$$

$$W_0=W/2tg\theta \tag{4}$$

A_0 is ligament area . $W_0=W/2tg\theta$. θ is the wedge angle of the test set-up. As shown in Figure 4, W is the area under P-CMOD curve in the ① method. In the ② method and ③ method, $W=W_1+W_2$. W_2 is the area under the part of the tested P-CMOD curve before the fitted tail section of curve. W_1 is the area under the fitted tail section curve. The formula for calculating W_1 by power function is as formula (5), while by exponential function is as formula (6):

$$W_1=\int_{CMOD_1}^{\infty}\beta(CMOD)^{-\lambda}d(CMOD)=\frac{\beta}{(\lambda-1)(CMOD_1)^{(\lambda-1)}} \tag{5}$$

$$W_1=\int_{CMOD_1}^{\infty}me^{-n(CMOD)}d\delta=\frac{m}{ne^{nCMOD_1}} \tag{6}$$

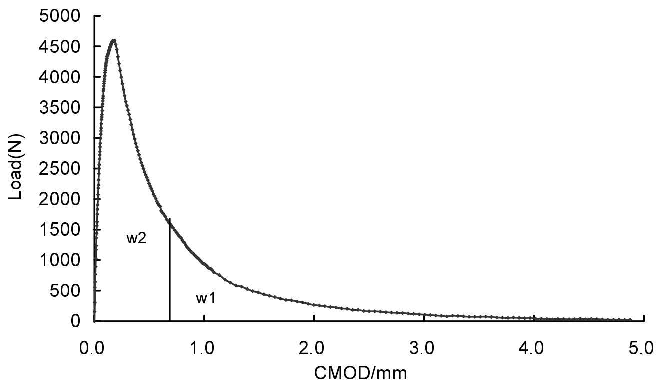


Figure 4. P-CMOD curve by wedge-splitting test.

2.3 *Comparative Analysis of the Fracture Energy Calculated by Different Methods*

The fracture energy G_F calculated by the above three methods are shown in Table 2. According to Table 2, the G_F calculated by method ① < the G_F calculated by method ②<the G_F calculated by method ③.

The G_F calculated by method ① was the smallest because of not considering the influence of tail section curve. Compared with the peak load between 5.03kN to 24.21kN, the end point of tested load existed between 0.18kN to1.89kN which can be re-

Table 2. Comparison of the G_F obtained by different methods.

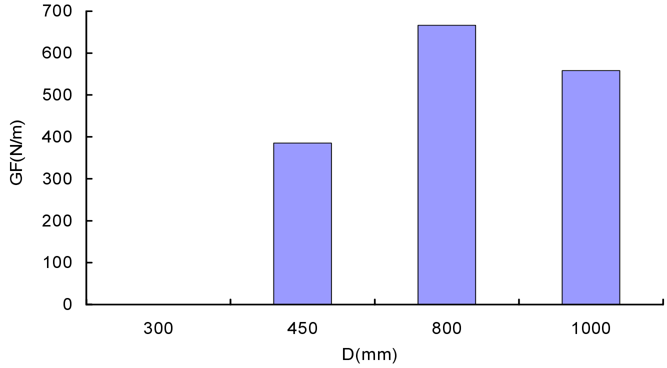
Speci-men	Categ-ory	D	G_F by Method ①	G_F by Method ②	G_F by Method ③
		mm	N/m	N/m	N/m
WS-d-1	Dam concr-ete	450	362.1	385.5	514.2
WS-d-2		800	598.1	666.3	819.9
WS-d-3		1000	516.8	558.2	633.8
WS-w-1	Wet-screened concr-ete	300	203.2	218.6	243.7
WS-w-2		600	354.1	373.3	439.8
WS-w-3		800	484.1	523.1	667.0
WS-w-4		1000	369.4	423.6	562.1

garded approaching to zero load. Therefore the obtained GF was a good agreement with the actual fracture energy. The GF calculated by method ③ was overestimated because two reasons: one was the tail section curve fitted by power function descended slowly than the corresponding tested curve, another is the CMOD of fitted tail section curve approaching infinity compared with the tested maximum CMOD used in method ①. The tail section curve fitted by exponential function descended rapidly than the corresponding tested curve, which led to the calculated GF being smaller. However, the CMOD of fitted tail section curve approaching infinity compared with the tested maximum CMOD led to the calculated GF overestimated. In sum, the GF calculated by method ② is possibly the nearest to that calculated by the corresponding tested P-CMOD curve. The results in Table 2 confirmed this point. So the GF of dam concrete and wet-screened concrete were identified by the averaged P-CMOD curve of which the tail section curve was fitted by the exponential function for each specimen group.

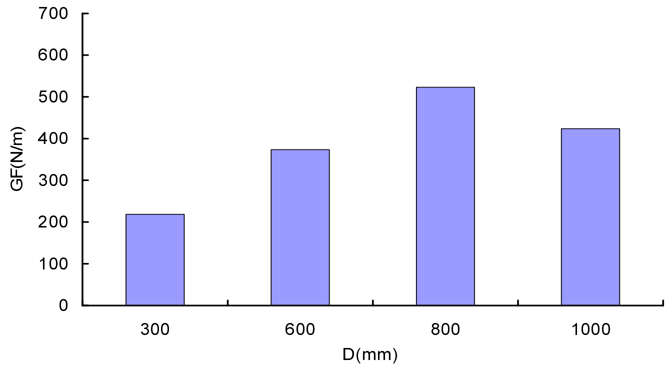
3 DISCUSSION OF THE FRACTURE ENERGY OF DAM CONCRETE AND WET-SCREENED CONCRETE

The G_F of different sizes specimens of dam concrete and wet-screened concrete were shown in Figure 5. It can be seen that G_F of these two kinds of concrete increased with an increase of the specimen size and the asymptotic behavior over the size was found. It also showed that G_F of dam concrete was larger than that of wet-screened concrete over the same specimen size.

Recently, some scholars (Duan K. et al. 2003) investigated the size effect of G_F from the boundary conditions of specimen. The boundary effect on fracture energy of dam concrete and wet-screened concrete would be tried in further study.



(a) Dam concrete



(b) Wet-screened concrete

Figure 5. Comparison of the G_F of different sizes specimens of dam concrete and wet-screened concrete.

4 CONCLUSIONS

The measured maximum CMOD value of some specimens which were included in our 7 groups wedge-splitting specimens with different sizes for dam concrete and wet-screened concrete exceeded capacity of the displacement sensor (5mm). It led to CMOD values distorted at the tail section of the tested P-CMOD curves for some specimens. The tail section curve need to be fitted, so that a complete P-CMOD curve can be got for calculating G_F.

The comparison between the fitted tail section curve by power function or exponential function and the corresponding tested complete curve showed that the fitted tail section curves by these two functions were a good agreement with the corresponding tested curves. The area enclosed by the fitted tail section curve by power function was some larger than that by the tested curve and the fitted tail section curve descended slowly than the corresponding tested curve. The area enclosed by the fitted tail section curve by exponential function was less than that by the tested curve and the fitted tail section curve descended rapidly than the corresponding tested curve.

Three methods were employed to calculate the fracture energy of dam concrete and wet-screened concrete: ①Calculated G_F by the tested P-CMOD curve for each companion specimen, then averaged the results and got the G_F for each specimen group.

② Calculated G_F by the averaged P-CMOD curve of which the tail section was fitted by exponential function. ③ Calculated G_F by the averaged P-CMOD curve of which the tail section was fitted by power function. It was shown that the G_F obtained by method ① was slightly small, but mostly close to the actual value. The G_F obtained by method ③ was some larger. The G_F obtained by method ② was the nearest to the result calculated by the originally tested complete P-CMOD curve. So the fracture energy of dam concrete and wet-screened concrete were identified by the method ② .

It was shown that G_F of dam concrete and wet-screened increased with an increase of the specimen size and the asymptotic behavior over the size was found. It was also shown that G_F of dam concrete was larger than that of wet-screened concrete over the same specimen size. The boundary effect on fracture energy of dam concrete and wet-screened concrete would be tried in further study.

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REFERENCES

Duan, K., Hu, X.Z. & Wittmann, F.H. 2003. Boundary effect on concrete fracture and non-constant fracture energy distribution. *Engineering Fracture Mechanics*. 70:2257-2268

RILEM Draft Recommandation(50-FCM). 1985. Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. *Materials and Structures*. 23 (138): 457-460

Xu, S.L., Bu, D. & Zhang X.F. 2007. Determination of fracture energy of concrete using wedge-splitting test on compact tension specimens. *Journal of Hydraulic Engineering*. 38(6):683-689

Zhao, Z.F. 2004. Research on fracture behaviors of dam concrete based on cohesive force of cracks. *Postdoctoral Research Report of Tsinghua University and China Gezhouba(Group) Corporation.*

Zhao Z.F., Yang L.J., Zhao Z.G. & Zhu M.M. 2009. Test Data Processing Method of Fracture Experiments of Dam Concrete for Inverse Analysis. In Yuan, Y., Cui, J.Z. & Mang,H.A. (eds). *Proceedings of the International Symposium on Computational Structural Engineering*, *Shanghai, 22-24 June* 2009. Springer.

Zhou, H.G., Li, Q.B. & Zhao Z.F. 2004. Research on fracture simulation of mass concrete cracks. *Cooperative Research Report of China Gezhouba(Group) Corporation, Tsinghua University and Yantai University*.