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THE INFLUENCE OF THE REDUCTION METHODS OF THE CONCRETE HARDENING TIME ON THE PARAMETERS OF THE GENERATED ACOUSTIC EMISSION SIGNAL MEASURED IN PLAIN AND IN HIGH STRENGTH CONCRETES

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Results of the Acoustic Emission (AE) measurements including: AE counts sum, averaged AE event power and averaged AE events spectral pattern are presented in dependence on the concrete mixture type and on the used thermal treatment method. Six compositions differing in the compression strength were examined. Four of them were those of plain concrete and the remaining two were silica — fume modified compositions. The results let the authors to conclude that there is a correlation between the two AE signal parameters: the AE counts sum and the averaged AE events spectral pattern and the applied thermal treatment procedure and, further, that the nature of the so induced changes of the AE parameters is similar for all the six concrete compositions tested.

1. Introduction

The stress wave caused by the energy release in stressed solids is called the Acoustic Emission (AE) effect. In concrete, the major AE sources are: crack growth, crack formation and friction processes. The nature of the AE signal generation enables the inspection of the state of constructional elements under the mechanical load. The frequency band of the AE signal generated in concrete elements is considered to lie approximately within the limits 10 kHz – 1000 kHz and, respectively the AE activity duration may vary from miliseconds to several days. The AE signal is measured by a piezoelectric sensor coupled to the element under test. The commonly used AE activity parameter is called "AE count rate" and denotes the number of crossings over the preset level by the AE signal. When the most common form of the AE event — a damped sinusoid is considered, the dependence between the AE signal amplitude A_m the centre frequency f_0, the count rate N_c and the preset signal level A_t can be described by the formula [1]:

$$N_c = f_0/\alpha_1 \ln(A_m/A_t), \tag{1}$$

where α_1 is the damping factor of the oscillations within the AE event.

Some authors have investigated the dependence between the compression strength of the concrete elements and the AE count sum registered during the process of loading [1–3, 5]. For the quasi-axial compression test made on 100 mm cubes, for which the 28 days compressive strength was designated within the range of 25 – 65 MPa, it was found that the total count sum $\sum N_{\mathrm{EA}}$ registered during the entire compression test depends on the composition compressive strength, R, according to the formula [4]:

$$\sum N_{\mathrm{EA}} = 814.8 \cdot R^2 - 55121 \cdot R + 10^6. \tag{2}$$

The power of the EA signal is proportional to the square of the averaged value of A_m within the measuring cycle Δt. The latter AE parameter is less preferred for the description of the AE generation process because it is affected by the scattering and damping effects caused by internal heterogenities of the tested material. However, there is also a correlation between the spectral patterns of the AE sources and the mechanical properties of the investigated object. The spectral characteristic of the AE signal registered by the AE sensor can be described by the following model [6]. The crack area generating EA is substituted by the inclusion zone V_0^*. The zone can be characterized by the same elastic constants as the remaining body with the addition of the non-elastic coefficient $\beta_{ij}^*(x,t)$. The latter should be put in the formula describing the displacement tensor in the discussed body when the displacement was activated by a Gaussian — shape disturbance of the local stress equilibrium. In this case the frequency-domain response registered by the sensor that converts the displacement appearing along the z axis into an electrical signal characterised by the electric potential V, can be described with the following formula:

$$|V(\omega)| = \frac{2\mu\Delta\varepsilon_{33}^* + \lambda\Delta\varepsilon_{33}^*}{4\pi\varrho r v_L^3} V_0^* P_0 \exp(-\omega^2\tau^2), \tag{3}$$

where: ω — pulsation of the frequency-domain EA signal registered by the sensor, Δ — "source rise time" equals 4τ [s], ε_{33}^* — component of the displacement vector used to characterize the inclusion zone V_0^* and proportional to the displacement direction, ϱ — material density, r — AE source — sensor distance, v_L — dilatation wave mode velocity, λ, μ — Lamé constants of the investigated body, P_0 — coefficient characterizing the sensivity of the AE sensor within the arbitrary chosen AE registration frequency range.

The parameter $|V(\omega)|$, averaged for an equal number of AE events registered during the experiment and calculated for certain values of the frequency $f = 2\pi\omega$, was by the authors of this paper called the averaged AE event spectral pattern, and used as the characteristic parameter for the investigated compositions. In the following chapters, the correlation between the total count sum $\sum N_{\mathrm{EA}}$ and the averaged AE event spectral patterns, registered before and after the heat treatment on dependence on the compression strength of different concrete compositions, is presented.

2. Experimental

Six concrete compositions differing in their compressive strength were prepared for the investigation. The compositions labelled 1, 3, 5 were based on crushed aggregates and the remaining three ones were based on river aggregates. A plasticizer was added to the compositions labelled 3, 4, 5, 6; silica fume was added to the compositions labelled 5 and 6. The water to cement ratios for the mixes 1 to 6 were: 0.6, 0.6, 0.45, 0.45, 0.3, 0.3. Each of the composition reached the maturity in one of the four following respects: staying at room temperature within 28 days or passing one of the three schemes of thermal treatment: "mild", "intermediate" and "rapid". The specimens were dismantled 1.5 hour before the start of the thermal treatment. In all schemes of the thermal treatment the same temperature levels were applied. The "mild" cycle lasted for 9.5 hours. The duration of the "intermediate" cycle was 40% of the "mild" one and that of the "rapid" cycle was 25% of the "mild" one. The increase coefficients of temperature vs. time were for the three cycles mentioned as follows: 20, 24, and 30 degrees per second. For each of the compositions the compressive strength was measured for ten cubic $100 \times 100 \times 100$ mm specimen by a quasi-axial compression test. In addition, the compression test was performed for the following three groups of specimen series: a) 28 days maturity under normal conditions; b) immediately after thermal treatment; c) 28 days maturity after thermal treatment. For ten specimens of each of the groups described above, the acoustic emission parameters were measured during the compression test. The AE measurements were made using a broadband AE sensor of type WD (Phycical Acoustic Corp., USA), an Acoustic Emission Analyser Type EA 100 and the 2.5 MHz A/D converter computer extension card. The process of the event recording was activated when the applied stress in the loaded sample reached 0.6 of the estimated rupture, shown in first column and in the first six rows of Table 1.

The following AE parameters were registered for further investigation: a) total AE counts sum registered during the compression test; b) 50 bytes long spectral patterns of AE events captured by the A/D converter card. Ca. 50 spectral patterns were recorded during the loading of each specimen. The consecutive bytes in the registered spectral patterns represent the AE signal power in the consecutive 20 kHz — wide subranges of the 1 MHz range of the analysed spectrum. It was proved after the registration that the dispersion of the averaged subrange power levels, derived from 100 recorded waveforms, is less than 10% when the different 100 — member sets of waveforms are averaged. Therefore, a common spectral pattern could be obtained for each concrete composition regardless of the number of specimens used to derive the 100 — member waveforms set. Using the averaged AE spectral patterns, two parameters were calculated. The first one was the average AE events power. To calculate this parameter, the power levels registered in all subranges were totalised. The second parameter was the average ratio of the AE

Table 1. The influence of the heat treatment scheme to the measured parameters for six investigated concrete compositions.

Composition Code	Compressive strength [MPa]	Strength rel. to measure in norm. cond. [%]	AE count sum [$N \times 1000$]	Count sum rel. to measure in normal cond. [%]	Average AE events power [arb.u.]	ev. power rel. to measure in norm. cond. [%]	Coeff. M/H [–]	Coeff. M/H average for maturing mode [–]
1	2	3	4	5	6	7	8	9
Hydration process at room temperature								
N1	25.9		277		174		1.25	
N2	24.4		216		183		0.91	
N3	34.8	100%	139	100%	210	100%	1.29	1.10
N4	35.9		176		176		1.14	
N5	63.6		886		179		0.87	
N6	52.1		471		145		1.65	
Rapid heat treatment								
R1	11.7	45	50	18	139	80	1.54	
R2	9.4	38	37	17	156	85	1.23	
R3	13.3	38	49	35	150	71	1.58	1.49
R4	12.8	35	19	10	156	89	1.57	
R5	45.8	72	370	42	166	93	1.46	
R6	36.3	70	485	103	156	108	1.56	
Rc1	23.4	90	343	124	163	94	1.00	
Rc2	19.5	80	302	140	151	82	1.07	
Rc3	25.3	73	198	142	162	77	1.72	1.27
Rc4	22.3	62	183	103	161	91	1.38	
Rc5	48.6	76	439	49	148	83	1.14	
Rc6	40.3	77	442	93	149	103	1.29	
Intermediate heat treatment								
I1	11.5	44	50	18	134	77	1.70	
I2	11.8	48	32	15	130	71	1.75	
I3	16.6	48	60	43	161	77	1.73	1.73
I4	17.3	49	61	35	144	82	1.81	
I5	52.0	82	407	51	144	80	1.71	
I6	44.0	84	357	76	146	101	1.61	
Ic1	21.1	81	374	135	148	85	1.20	
Ic2	20.4	84	355	164	147	80	1.11	
Ic3	29.3	84	213	153	144	69	1.41	1.20
Ic4	25.3	70	199	113	139	79	1.40	
Ic5	54.9	86	380	43	156	87	1.07	
Ic6	47.0	90	355	75	161	111	1.05	

Table 1. [cont.]

1	2	3	4	5	6	7	8	9
Mild heat treatment								
M1	13.5	52	80	29	150	86	1.71	1.58
M2	13.1	54	85	39	157	85	1.52	
M3	15.6	45	71	51	151	72	1.50	
M4	22.7	63	95	54	159	90	1.65	
M5	53.8	85	246	28	157	88	1.70	
M6	42.8	82	217	46	159	109	1.46	
Mc1	22.7	88	303	109	155	89	1.11	1.38
Mc2	22.8	93	318	147	156	85	1.02	
Mc3	24.2	69	194	139	158	75	1.67	
Mc4	26.7	74	181	102	143	81	1.52	
Mc5	57.2	90	257	29	159	89	1.27	
Mc6	46.8	90	266	56	158	108	1.74	

event power measured within the frequency range 50 – 400 kHz to that one measured in the frequency range 400 kHz to 800 kHz. To calculate this second parameter, the power levels registered in the two subranges mentioned above were totalised and then their ratio was calculated. The latter parameter was denoted as M/H. One of the aims of this investigation was to determine whether the structural and the maturing conditions correlate with the AE event spectral pattern changes; this correlation is represented with M/H parameter. The measured AE counts sums and rupture forces, measured for all composition sets of the specimens did not differ from each other by more than 10% within the set.

The basic composition parameters as well as the major test results are collected in Table 1. The following code was used to determine the sample series type listed in the table. The n1...n6: the 28 days maturing process under normal conditions; r1...r6: the maturing process when the rapid thermal treatment was applied and the compression test was performed immediately after the heating; rc1...rc6: the maturing process when the rapid thermal treatment was applied and the compression test was performed 28 days after the heating; i1...i6: the maturing process when the intermediate thermal treatment was applied and the compression test was performed immediately after the heating; ic1...ic6: the maturing process when the intermediate thermal treatment was applied and the compression test was performed 28 days after the heating; m1...m6: the maturing process when the mild thermal treatment was applied and the compression test was performed immediately after the heating; mc1...mc6: the maturing process when the mild thermal treatment was applied and the compression test was performed 28 days after the heating. The data presented in Table 1 include: rupture level measured in the specimen during the compression test, registered AE count sum, average AE event power and the M/H parameter. To enable the further analysis, the relative changes of the above parameters in respect to the values measured in the n1..n6 series were also put in the Table 1.

3. Discussion of the results

The relation of the total count sum $\sum N_{\mathrm{EA}}$ vs. the registered compressive strength R_N measured for the series n1..n6 shows good agreement with the formula (2) which was found for the compositions hardening at room temperature. In the other series, the thermal treatment caused a loss of the compressive strength R_T. For all the six investigated compositions, the averaged loss of the compressive strength ratio, calculated as R_T/R_N equalled ca. 50% for the measurements made immediately after the heat treatment. The loss was reduced to ca. 20% for the measurements made 28 days after the heat treatment. It is worthy of mentioning that the relative changes of $\sum N_{\mathrm{EA}}$ measured after the heat treatment and related to the normal hardening conditions were similar within the majority of the investigated compositions. For higher losses of compressive strength, there is a good agreement between the AE counts sum and the compressive strength changes. The dispersion of the AE counts sum rises dramatically for minor compressive strength losses measured for the samples after 28 — days curing. The results described above and the possible linear regression curve parameters are shown in Fig. 1.

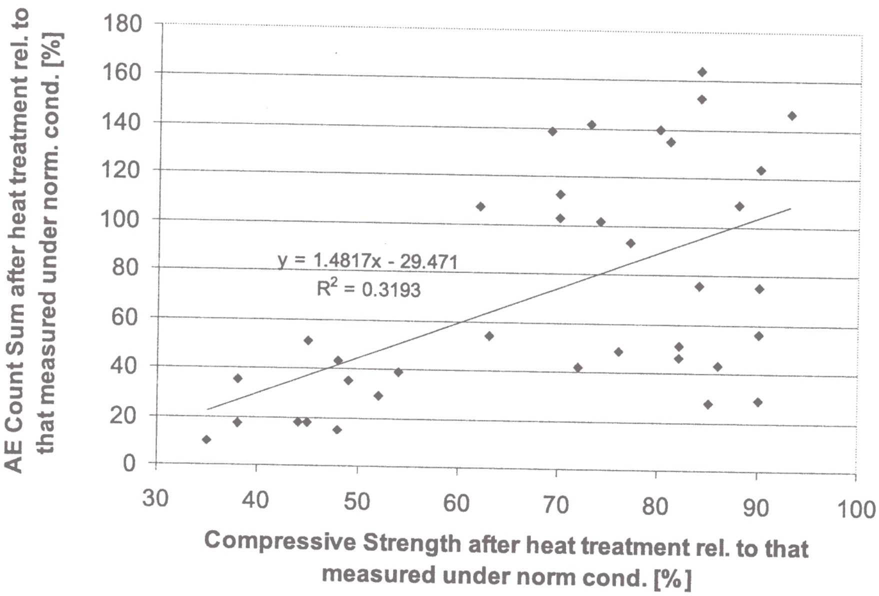

Fig. 1. The dependence of the AE count sum measured in the samples after thermal treatment and related to the AE count sum measured in samples hardened under normal conditions versus compressive strength ratio measured in the similar two sample series.

The investigation results presented in Table 1 state that there is no clear correlation between the averaged AE event power and the hardening conditions. In most of the compositions a slight loss of the averaged AE event power could be observed when thermal treatment was applied. The spectral contents of the AE signal generated in stressed concrete compositions, however, changes proportional to the degree of damages caused by the thermal treatment. To capture these changes, 100 waveforms of the AE events, each

100 bytes long were registered for every composition and heat treatment scheme. After the computer processing of this data averaged spectral patterns corresponding to the described sample series were constructed. The specific parameter, denoted M/H, was chosen to find if there is any correlation between the compression strength loss caused by the heat treatment (defined as R_N/R_T) and the averaged AE event spectral patterns. The M/H parameter was defined as the ratio of the averaged power in the range 50 kHz – 400 kHz to the averaged power in the range 400 kHz – 800 kHz for the registered AE events. The data presented in the Table 1 let the authors to point out the following conclusions.

The increase of the compressive strength causes an increase of the AE signal power in the high frequency range H. The high frequencies are generated in areas in that the local stress level had reached the relatively high value. This relation is shown in Fig. 2.

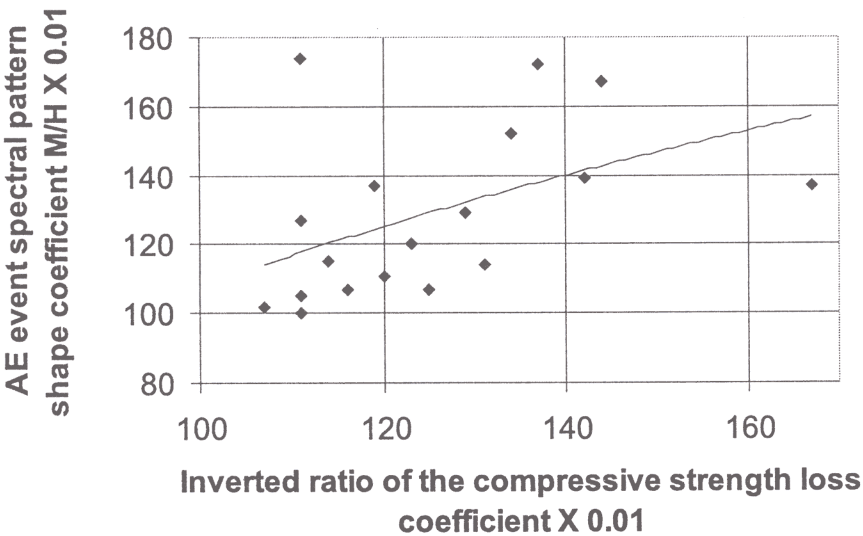

Fig. 2. The correlation between the spectral pattern shape coefficient M/H and the inverted compressive strength loss coefficient defined as R_N/R_T.

Typical spectral patterns of the averaged AE event registered for the three levels of the compression strength loss discussed above are shown in Fig. 3.

The compositions n1..n5, hardened at normal conditions generated a considerable amount of the AE event power in the high frequency range and, therefore, the M/H coefficient for these compositions was relatively low (approx. 1.0). In the compositions for which the heat treatment was applied and, additionally 28 days of hardening was effected, the average M/H coefficient level was within the range of 1.1 – 1.5. If the M/H coefficient was measured immediately after the heat treatment when most of the significant loss of the compressive strength occurred, the M/H coefficient exceeded the 1.5 level. Therefore the M/H parameter, derived from the AE signal, might be applied as a measure of the degradation of the concrete structure.

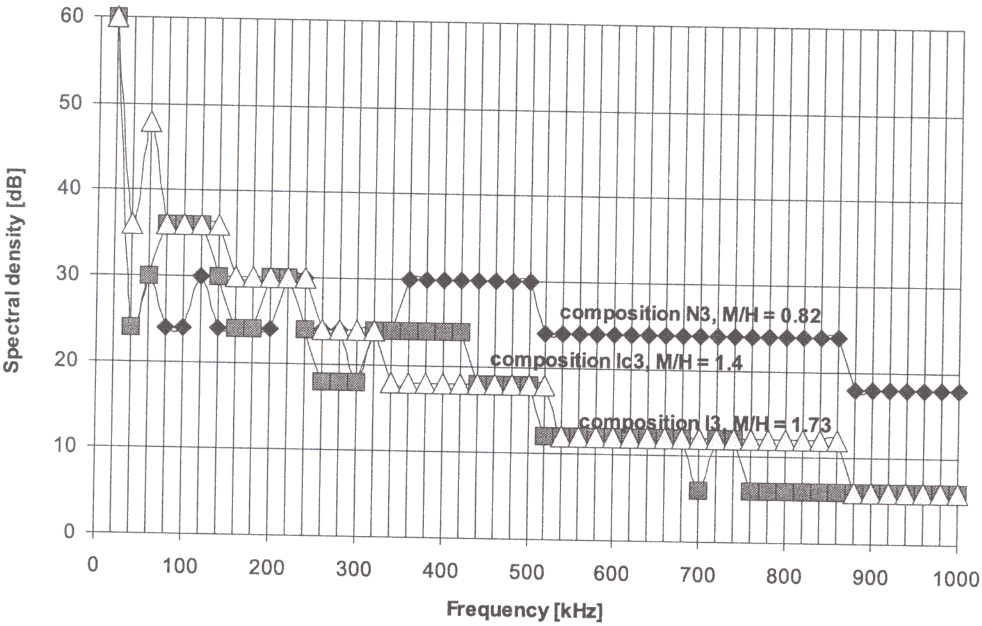

Fig. 3. Three averaged AE event spectral patterns registered in the composition hardened under normal conditions (N3), 24 days after the heat treatment (Ic3) and immediately after the heat treatment (I3).

4. Conclusions

The presented measurement results show that:

a) a generally higher loss of the compression strength caused by faster temperature changes during the heat treatment implies a higher decrease of the AE counts sum (as shown in Fig. 1),

b) regardless of the heat treatment method applied, the registered AE counts sum value in high strength concrete compositions is 200–300% higher than in weaker plain concretes matured under the same conditions.

The above conclusions let the authors state that the AE counts sum may be applied as a parameter correlating with the mechanical strength level of the investigated compositions.

The higher level of the compressive strength causes an increase of the AE signal power in the high frequency range H. The high frequencies are generated in the areas in that the local stress level reaches a relatively high value (as shown in Fig. 2); therefore the average spectral pattern of the AE events registered during the compression test also depends on the mechanical strength of the tested composition. This both the AE parameters described above can be useful in the comparison of the mechanical properties of concrete compositions.

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