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# Aging effects on laminated rubber bearings of Pelham bridge

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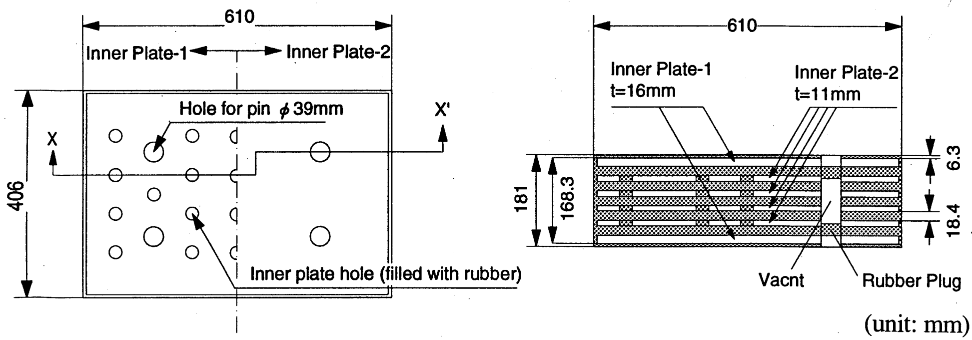
ABSTRACT : Durability of rubber bearings is essential for the safety of a seismically-isolated fast breeder reactor over its life cycle of up to several decades. In this regard, the authors have been involved in a joint UK-Japan research program initiated in 1994 to study structural and material characteristics of the natural rubber laminated bearings extracted from a some 40 year old bridge: Pelham Bridge in Lincoln, UK. This paper summarizes several major findings from structural tests of the bearings as well as mechanical and chemical tests at the material level.

## 1. OVERVIEW

Thermally accelerated aging is generally used for evaluating the aging effects on laminated rubber bearings in the natural environment, though the consistency between actual and accelerated aging effects is yet to be confirmed. In this regard, a UK-Japan joint research program [1] was initiated to study structural and material characteristics of 40 year-old natural rubber bearings at a road bridge, Pelham Bridge, built in 1957 in Lincoln, UK: the first bridge in the UK in which laminated rubber bearings were used to avoid thermal stress due to temperature changes. No serious trouble has been reported so far regarding the serviceability of the rubber bearings. The average temperature of the site is approximately 10 °C. In 1994, eight rubber bearings on one of the bridge portal support were replaced with new ones, and the old bearings were subjected to tests carried out both in the UK and in Japan. The present paper provides the results obtained from the tests in Japan.

Horizontal and vertical sections of a typical rubber bearing are shown in Fig. 1. The rubber bearings consist of five natural rubber layers with a thickness of 18.4 mm, six steel inner plates and two thinner rubber layers with a thickness of 6.3 mm. The side is also covered with thin rubber. While in service, the bearings were connected to the bridge portal (or girder) by four dowel pins put into thicker inner plates (Inner Plate-1) at the upper and lower ends. The rubber bearings were exposed to neither rain nor severe sunshine because of being beneath a wide road pavement.

Fig. 2 shows the locations of the rubber bearings tested. Five of the eight bearings removed were tested in Japan. Loading tests on the overall structural behavior of bearings were carried out using two bearings, No. 2 and 7. Material tests were performed with bearing No. 3, 5, and 8, to examine mechanical and chemical properties. Additionally, thermally accelerated aging tests using center portions of the bearings were performed based on the test results, obtained from as-aged bearings, that the center portion is considered not affected by oxygen attack.




(a) Plan (b) X-X' Section

Fig. 1: Rubber Bearing at Pelham Bridge

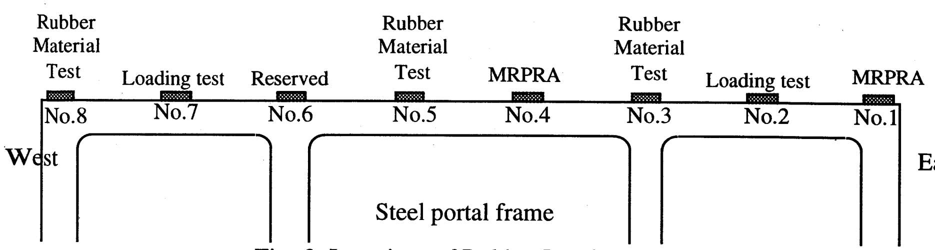
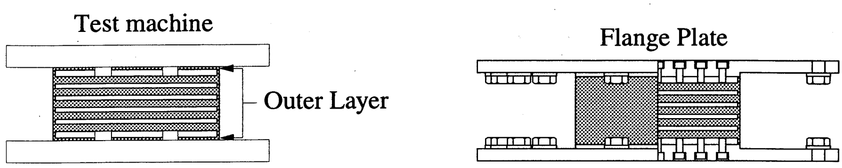



Fig. 2: Locations of Rubber Bearings Tested

## 2. STRUCTURAL LOADING TESTS

The design specifications for the bridge bearings are shown in an article of *Rubber Development* published in 1957 [2]. The shear and compressive stiffnesses were designed as 10 tonf/inch (3.94 tonf/cm) and 1,000 tonf/inch (394 tonf/cm), respectively. Shear strain capacity was expected to be 170 %. Shear and compressive tests of bearings were reportedly executed. However, there is no description about the test conditions except photographs taken during the tests. According to the photographs, the rubber bearings are supposed to have been tested without dowel pins, and the outer rubber layers with a thickness of 6.3 mm were active. In another paper [3], we found stiffness measurements of 9.4 tonf/cm (3.70 tonf/cm) and 1,200 tonf/inch (472 tonf/cm) for shear and compression, respectively, though no further test conditions are given here, either. The shear stiffness of 9.4 tonf/cm, 6% smaller than the design value of 10 tonf/inch shown above, is regarded to be the basis for comparison with the results discussed below.

In 1995, structural loading tests were performed using the rubber bearing No. 2 and No. 7. In the first place, shear stiffness tests were performed in a set-up shown in Fig. 3 (a). The bearings were placed between test machine loading plates, and a nominal force of 60 tonf was applied. When using this set-up, the outer thin rubber layers were active. Considering the lack of information on initial testing, the loading displacement was chosen as 1.25 inch, corresponding to a shear strain of 30%. The loading directions were longitudinal and transversal. In the next step, the outer thin rubber layers were removed and new outer flange plates were bolted to the inner steel plates as shown in Fig. 3 (b). Shear stiffness measurements were obtained using this set-up at the shear strain of 30% as well. Finally, shear tests up to failure were conducted in the longitudinal direction.




(a) With outer rubber layers (b) Without outer rubber layers

Fig. 3: Specimen for the loading test

The shear stiffness obtained as in Fig. 3 (a) varied from 3.30 tonf/cm to 3.49 tonf/cm, while the results under the condition of Fig. 3 (b) from 3.93 tonf/cm to 4.32 tonf/cm for the two bearings. The latter test results should be normalized by the rubber thickness ratio of Fig. 3 (a) to Fig. 3 (b) to be compared with the initial tests [2] that were likely conducted under the condition of Fig. 3 (a). If adjusted, the shear stiffness obtained from both configurations would range from 3.30 to 3.79 tonf/cm. It should be noted that these results, obtained some 40 years after fabrication, are not significantly different from the initial test result of 3.70 tonf/cm (the difference is less than +3% at the most), though many of recent studies elsewhere predict overall stiffness increase of 10-20% over similar service periods. The bearings failed at a shear strain of 160% at the adhesive portion combining rubber and steel (Fig. 4). This value is viewed almost to satisfy the originally expected deformation capacity.

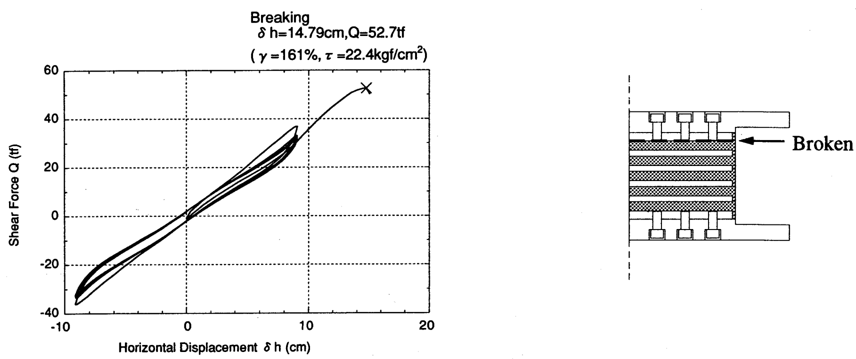
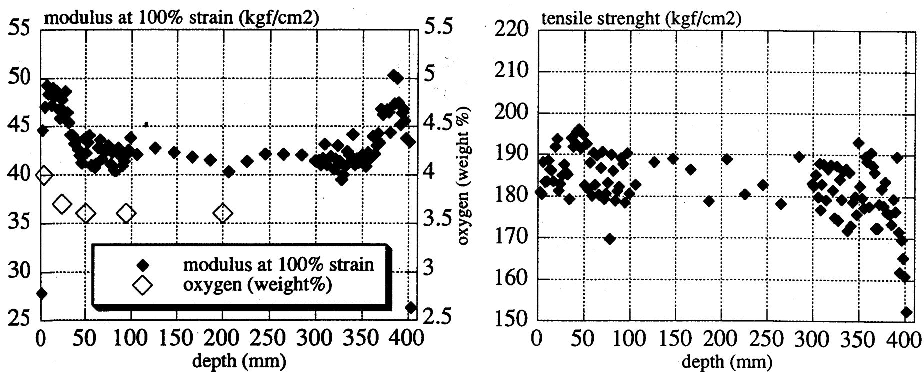



Fig. 4: Result of shear failure test

## 3. RUBBER MATERIAL TESTS

### *3.1 Tests on rubber material aged under natural conditions*

In 1995, a number of specimens were cut from the Pelham Bridge bearings (Nos. 3, 5, and 8) and subjected to tests to investigate both mechanical and chemical properties, each varying with depth from bearing sides [1]. The mechanical tests include measurements for hardness, tensile and shear moduli/strengths of rubber layers, and the adhesion properties at steel-rubber interfaces. The chemistry was analyzed for depth profiles of crosslinking density and oxygen ingress, as well as weight percentages of natural rubber, carbon black, sulfur, antioxidants, etc. Fig. 5 exemplifies typical depth profiles of tensile modulus at 100% strain and tensile strength, both obtained for No. 3 bearing. Fig. 5 (a) also includes the distribution of oxygen in percent by weight. Our measurements indicate that stiffness-related parameters such as hardness and modulus tend to be highest at bearing sides, decrease with depth up to some 50 mm, and stay considerably constant beyond that depth. It should be noted that this tendency also holds for the oxygen amount (Fig. 5 (a)). Based on these findings, the stiffness increase on rubber layer fringes can be attributed to oxygen ingress from outside of the bearings. Tensile strength measurements as shown in Fig. 5 (b), on the contrary, tend to decrease near the side surfaces. However, the depth showing property change is much less than those of stiffness-related parameters. The same can be said for the distribution of elongation at break.




(a) modulus at 100% strain (b) tensile strength

Fig. 5: Tensile Modulus/Strength Distribution of Bearing No. 3

### *3.2 Tests on rubber material under accelerated aging conditions*

Furthermore, a series of accelerated aging tests was performed focusing on changes in mechanical characteristics of the center rubber (which was viewed as not affected by the oxygen attack based on the findings in the previous section) heated at various temperatures for periods including those thought equivalent to 40 years in the natural environment. The tests took place in the following manner: (1) Portions A and B (Fig. 6) were cut out of rubber layers with steel plates attached on upper and lower rubber surfaces, (2) control tests for each layer were performed using dumbbell specimens taken from Portion B, (3) Portion A specimens from a number of layers were each heated in ovens at 70, 80, and 90 °C for designated periods (Accelerated Aging), and (4) hardness and tensile tests were performed on Portion A. Note that rubber layers were heated with steel plates on, so that oxygen ingress should be allowed only from side surfaces around each Portion A.

Table 1 summarizes the specimen names (i.e., the numbers of bearings and layers: No. 3-1, for example, denotes the rubber layer 1 cut from the bearing No. 3) subjected to heating as well as the length of heating in day. The heating duration for each specimen was determined by assuming an Arrhenius-type of equation on rate of aging:

$$\text{rate of aging} \propto \exp(-Q/RT) \qquad \text{eq. 1}$$

where Q means the activation energy, which for this study was assumed to be 20 (kcal/mol), R is the gas constant, and T denotes the absolute temperature. The curing temperatures were 70, 80, and 90 °C while curing time for each temperature was determined so as to correspond to real duration ranging from 20 to 135 years of aging at 10 °C (i.e., roughly the average temperature of Lincoln, UK). It should be noted that in determining the time scale in Table 1, Portion A specimens prior to heating were assumed to be 0 year of age.

Table 1: Test Conditions

| Time at 10℃ (year) | | 20 | 40 | 80 | 135 (40 at 20℃) |
|---|---|---|---|---|---|
| Specimen | Cured at 70℃ | No.8-4 | No.3-1 | No.8-4 | No.3-1 |
| | Curing Time (day) | 14.5 | 28.9 | 57.8 | 97.4 |
| Specimen | Cured at 80℃ | - | No.3-4 | - | No.3-5 |
| | Curing Time (day) | - | 12.6 | - | 42.4 |
| Specimen | Cured at 90℃ | - | No.3-4 | - | No.3-5 |
| | Curing Time (day) | - | 5.7 | - | 19.3 |

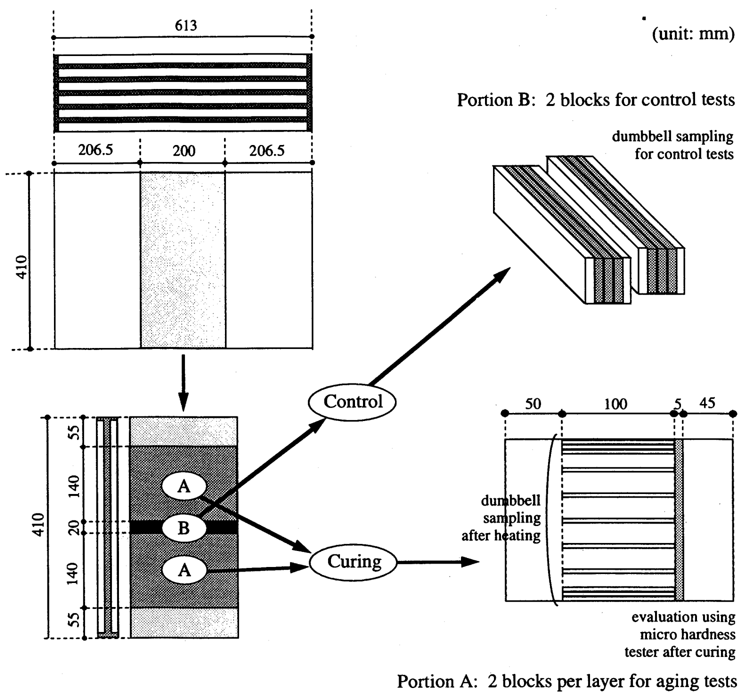



Fig. 6: Processing of Aging Test Specimens

Measurement profiles are summarized in Fig. 7, where depth 0 mm is the 'internal' side of Portion A specimens (the side next to Portion B, shown in Fig. 6), while depth 140 mm being the other side.

Tensile modulus at 100% strain measurements are compared in Figs. 7 (a) to 7 (c) for three levels of curing temperatures. Modulus measurements at 70 °C increase at smaller depths. This tendency becomes less evident as the curing temperature increases. The tendency for hardness of rubber, another stiffness-related property, was quite similar to that of the tensile modulus. As an example, hardness measurements obtained by International Rubber Hardness Degree (IRHD) method are shown in Fig. 7 (d). On the other hand, elongation and tensile strength at break near the surfaces were reduced by accelerated aging (only 70 °C results are shown in

Figs. 7 (e) and 7(f)). The affected depth varies roughly from 3 to 5 mm depending on the curing temperature.

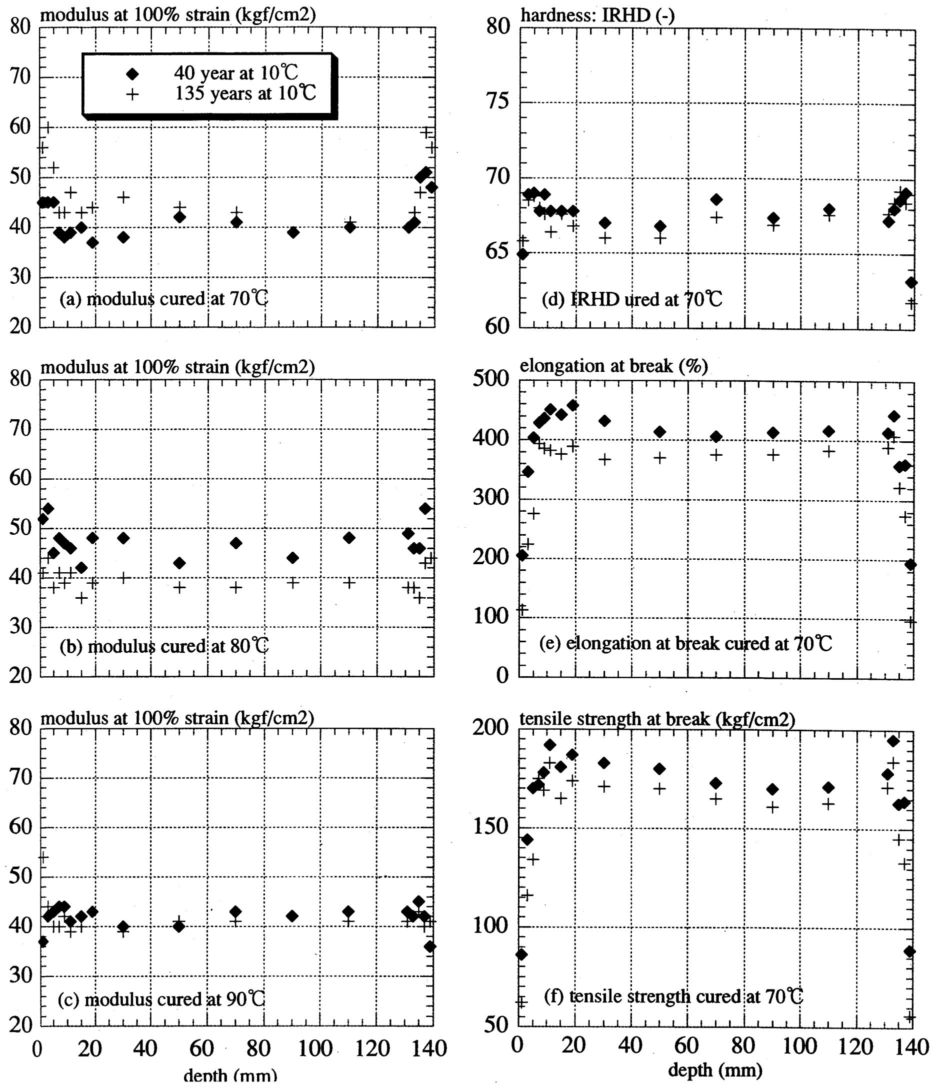



Fig. 7: Depth Profiles of Various Characteristics

Temporal changes in 100% tensile modulus and elongation at break are compared in Fig. 8 for two groups by depth: center and near-surface. In this figure, the measurements for the center portion are represented by those obtained at depths of 30, 50, 70, 90, and 110 mm while the near-surface data are measured at 3 and 137 mm: 3 mm from both sides of Portion A. In general, the center measurements remain constant in terms of time, and the modulus at 100% strain (though considerably scattering) tends to increase while the elongation at break decreases as time passes.

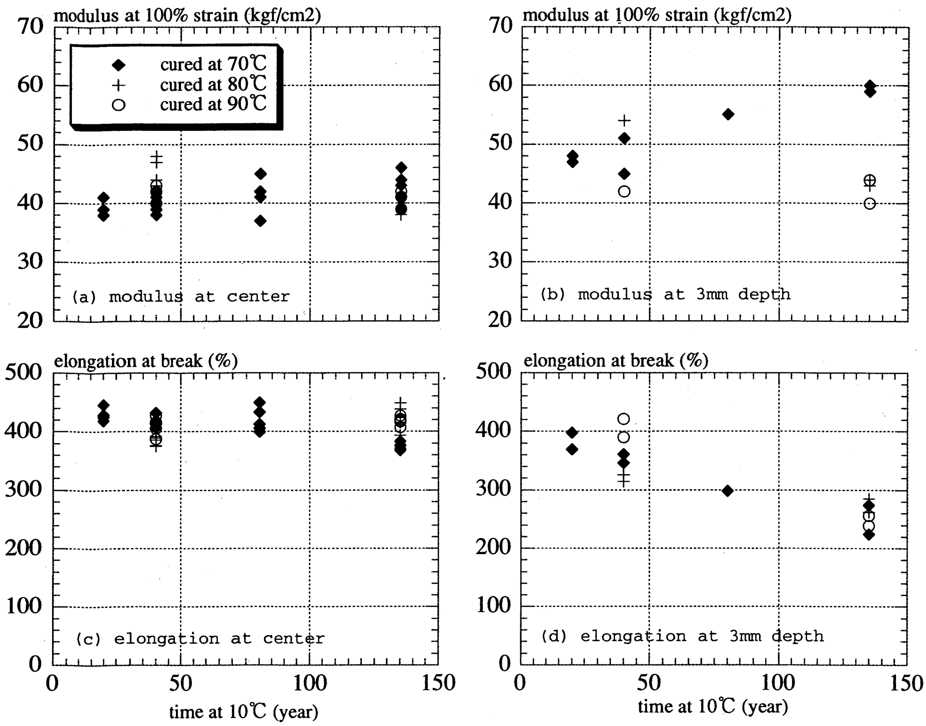



Fig. 8: Trends in Modulus and Elongation at Break at Center and 3 mm Depth

Furthermore, the 'depth of oxidation' [4] was estimated: the depth of oxidation is defined as a depth where the change in a mechanical property reaches a certain level compared to that of the internal portion of a rubber layer. To quantify the depth of oxidation, spatial distributions of mechanical properties such as in Fig. 7 were fitted using multi-dimensional linear equations on depth, and the depth of oxidation was estimated based on the regression results at the end of rubber layers.

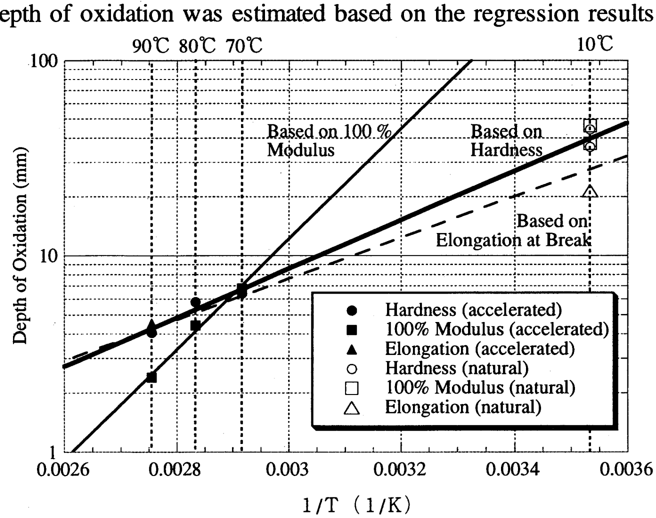



Fig. 9: Comparison of Depth of Oxidation Based on Various Mechanical Characteristics

Fig. 9 provides the relations between the reciprocal of the absolute temperature for curing (1/T) and the depth of oxidation (DoO) based on various properties (i.e., 0.25 degree change in measurements of a micro-hardness tester, 5% increase in tensile modulus at 100%, and -5% change in elongation at break). Comparing linear equations fitted to accelerated aging results on the $\log_{10}$ (DoO) vs. 1/T scale, extrapolating the relation based on hardness change (bold line) predicts the best the results under natural conditions (open circles), elongation-based prediction (broken line) slightly overestimates the actual results (open triangle), and the modulus-based regression (thinner solid line) highly overestimates the depth of oxidation shown with open squares.

## 4. CONCLUDING REMARKS

Taking account of the uncertainty in original test conditions, two types of set-up were used to measure the overall shear stiffness of 40-year old rubber bearings. At the most, the increase of stiffness over the service period is likely less than +3 %.

Stiffness-related parameters such as hardness and modulus showed increase at depths no larger than 50 mm, and elongation and strength at break measurements were less affected by oxygen attack than the stiffness-related measurements, based on the results from material samples under natural aging conditions.

The depth of oxidation in the natural environment could be predicted with some accuracy using results obtained from accelerated aging. However, the accuracy of prediction may vary according to the property on which the depth of oxidation itself is defined.


## ACKNOWLEDGMENTS

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