ELSEVIER

Cement & Concrete Composites 24 (2002) 73–78

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Retarding of corrosion processes on reinforcement bar in concrete with an FBE coating

A.B. Darwin, J.D. Scantlebury *

Corrosion and Protection Centre, UMIST, PO Box 88, Manchester M60 1QD, UK

Abstract

Fusion-bonded epoxy-coated rebar (FBECR) was studied by casting in a poor quality concrete and subjecting the specimens to a cyclic wet/dry exposure (monthly) using either 3.5% NaCl or demineralised water over a period of 12 months. On-going measurements of half-cell potentials were made together with regular visual observations. At the end of the test, the bars were removed for visual inspection and assessed for corrosion rate using weight loss. Variables examined included the presence or absence of a coating holiday (3 mm ∅) and the presence or absence of a chromate conversion coating. It was concluded that the FBECR provided a significant improvement in corrosion resistance that was further enhanced by the presence of the chromate conversion coating.

Keywords: Corrosion; FBE coating; Corrosion processes

1. Introduction

Epoxy-coated reinforcing steel was first used in a full-scale application in the construction of a four-lane bridge in America in 1973 [1] and has since been incorporated in more than 100,000 structures in North America alone, equating to over 2 million tons of epoxy-coated reinforcing steel [2]. Corrosion performance of fusion-bonded epoxy (FBE)-coated rebar over the long term in field structures has been monitored by various interested organisations including the Concrete Reinforcing Steel Institute. In these studies, it was concluded that epoxy-coated reinforcement was providing a high degree of protection in bridge decks where chloride content exceeded the corrosion threshold.

Reports have been made of failures in concretes incorporating FBE-coated rebar (FBECR) exposed to marine environments in as short a time period as 10 yr [3,4], the most well known of which being bridges in the Florida Keys that had been constructed using epoxy-coated rebar in the late 1970s [5]. The concrete cover on a couple of these bridges had begun to spall in isolated areas, often found in the region above the high tide mark where evaporation and wetting regimes create a zone of high chloride accumulation.

Since this time a number of investigators have concerned themselves with FBE-coated bar, their findings on its ability to prevent corrosion ranging from scepticism to almost unqualified endorsement [6–10]. The focus of this study, in continuation of previous research by the authors in this field [12,13], has been to determine whether an FBE coating will improve the reinforcement bar corrosion performance in concrete by subjecting it to an accelerated test regime, and to add to the debate above.

2. Experimental

The steel reinforcement bar used was from the same manufacturers batch. It was grit-blasted to Sa3 [11] at the FBECR manufacturer's plant and some bar treated with the standard chromate wash using both the company's normal production line processes and materials. The bars were then coated with Akzo Nobel Powder FBE to a thickness of 230 μm by heating the bar to a temperature between 230°C and 235°C, then passing it through a spray booth where electrostatically charged particles were deposited on it through a multiple gun array. Completion of the chemical bonding reaction, in

---

* Corresponding author. Tel.: +44-161-200-4841; fax: +44-161-200-4865.

E-mail address: scantlebury@umist.ac.uk (J.D. Scantlebury).

0958-9465/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0958-9465(01)00028-2

which cross-linking of the system was achieved, was caused by the residual heat of the reinforcement bar.

The bars were cut to 15 cm length and holidays of 3 mm diameter made in the majority of them with a flat-head drill bit. A nichrome wire was attached and the bar ends coated with an epoxy resin sealant. They were then weighed and encased in concrete (Fig. 1). The concrete's depth of cover was 32 mm. Its composition was, by weight, 1 part cement:2 parts sand:4 parts aggregate, with a water/cement ratio of 0.7. This mix created a concrete with a 28-day unconfined compressive strength of 28 N mm^2, described as a type C28 concrete [14]. From the literature it was found that cyclic wetting and drying with a 3.5% NaCl solution generated the most severe conditions [10]. Furthermore, the use of monthly cycles for the wet/dry periods was said to cause the greatest amount of corrosion [15], so it was determined that the concrete test specimens to be exposed to a corrosion-initiating environment would be placed in a monthly regime of wet/dry cycles in 3.5% NaCl solution. Reference to BS8110 [16] classifies the chosen exposure conditions as very severe. Neither concrete type nor chosen depth of cover meets the recommended protection criteria of this standard; this was done to accelerate conditions for corrosion in concrete.

Some test cells using rebar without an FBE coating were also made such that FBE performance might be compared. Flexcrete™ cementitious coating was applied where the rebar emerged from the concrete cover to prevent crevice-related complications [17].

A ponding system is normally used for cyclic testing, whereby an indentation is made in the top of the concrete specimen such that a reservoir of the exposure electrolyte may be made. Instead, a simpler method of placing the concrete specimens to a given depth in a tank containing the test solution was used. The depth of immersion of the concrete specimens was chosen to be 17 mm, such that the base of the reinforcement bar in the concrete test specimen was 15 mm above the level of the surrounding test solution.

Two types of test solution were used; demineralised water and 3.5% (wt) NaCl salt solution. The test period of each concrete specimen started with a 1-month placement in the given test solution environment. Total test time of the concrete specimens was 12 months. During this time, half-cell potential measurements of the bars were made weekly with a high internal impedance (10^8 Ω) digital voltmeter via a saturated calomel electrode placed on an absorbent pad on the upper face of the concrete specimens, which were also subject to periodic visual inspection. Experiments were carried out in triplicate.

With the end of the experimental run, the bars were removed from their encapsulant concrete, visually examined, and weighed after removal of any corrosion products by pickling in 50% hydrochloric acid containing hexamine as an inhibitor [7].

3. Results and discussion

The potential behaviour of uncoated and FBE-coated reinforcement bars may be seen in Figs. 2 and 3. The potentials of the FBE-coated bars without holidays are not included due to the high system impedance preventing measurement. The finding that the resistance of the system being measured was greater than 10^8 Ω informs us that, as concrete typically has a resistance of 10^5 Ω cm^2, the FBE coating must have been the provider of this high resistance. Its actual resistance will have been greater than 10^9 Ω cm^2 because the total area of FBECR exposed in the test specimen was of the order of 60 cm^2.

The bars in concrete test cells exposed to demineralised water tended to half-cell potentials of the order of -100 to $+100$ mV, indicating their passivity. All un-

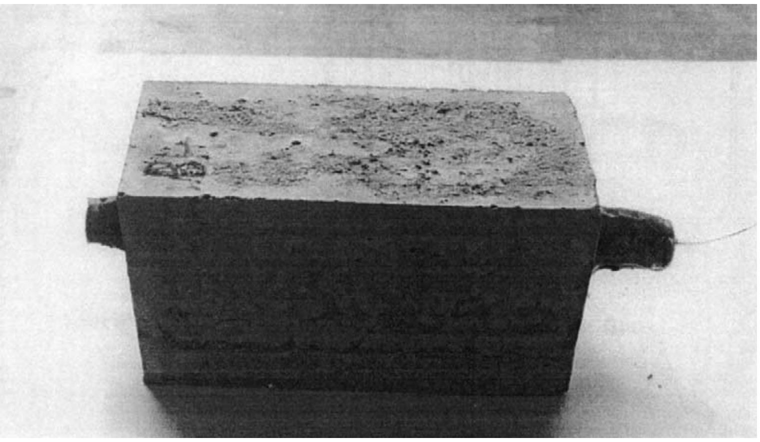

Fig. 1. Concrete test specimen with encapsulated reinforcement bar.

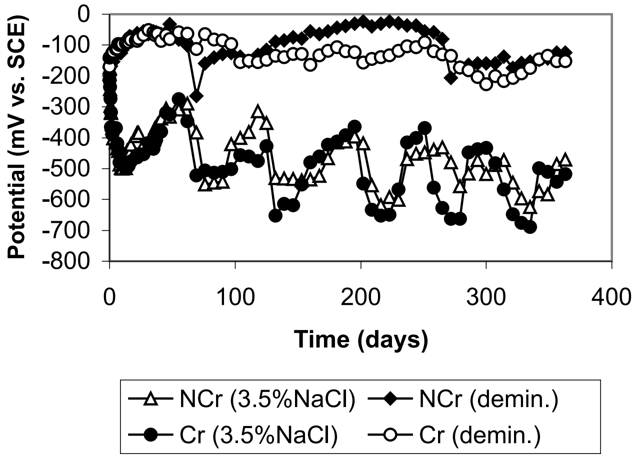

Fig. 2. Half-cell potentials of uncoated rebar during cyclic immersion.

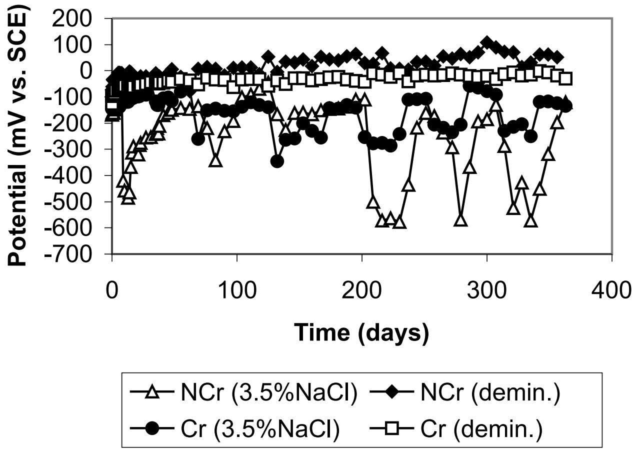

Fig. 3. Half-cell potentials of FBE-coated rebar during cyclic immersion.

coated bar brought into contact with the salt solution, irrespective of the presence of a chromate wash, drifted to more negative potentials. In the first month, readings below −280 mV (≈−350 mV CSE) were recorded, suggesting a significant probability that corrosion was taking place [18]. Also seen in the figures is the appearance of a cyclic fluctuation in the recorded potential, i.e., for a period of ≈1 month the potentials measured dropped substantially, then continued to increase and decrease over successive months. This periodic change correlated with the wet/dry cycle of immersion of the concrete specimens in salt solution. The sometimes drastic drops to more base potentials occurred when the specimens were immersed in the electrolyte after a month's dry cycle; sudden changes to more noble potentials occurred after removal of the concrete specimens from electrolyte for their dry cycle. It is believed that the noble shifts in potential are due to the drying-out of the porous concrete encapsulant around the reinforcement bar, thus slowing the corrosion process by increasing the effective ionic resistance between anodes and cathodes on the rebar. The negative shift in potential when the concrete specimens were placed back into solution may therefore be due to the reintroduction of electrolyte to increasingly salt-saturated concrete, allowing corrosion to take place more freely. The drying and wetting process in the concrete, and hence change in concrete resistivity, will have caused variation in the IR drop through the bulk concrete environment, and may have served to accentuate the potential shifts monitored.

The potential of the FBE-coated bar with chromate wash remained consistently more noble than −280 mV (Fig. 3), suggesting that it may not be corroding. After ≈6 months the non-chromated FBECR reached potentials which for the first time suggested probable corrosion of the bar. However, during the monthly dry cycles, the potentials of these bars moved to sufficiently noble potentials to indicate their passivity, behaviour different to that of the uncoated bars.

Concrete specimens partially immersed in demineralised water remained the same in appearance throughout the test. Concrete specimens cyclically immersed in salt solution displayed the progressive growth of a ring of salt deposit at or slightly above the level of the reinforcement bar in the specimen. There was no corrosion staining or cracking of any of the concrete specimens.

At the end of the testing period, the concrete cells were broken open to investigate the reinforcement bar. Both the chromated and non-chromated FBECR samples appeared essentially unchanged with no evidence of corrosion on the exposed FBECR steel substrate, irrespective of which solution it had been exposed to (Fig. 4), and no rust staining of the encapsulating concrete around the rebars.

Some delamination had taken place (Table 1). It may be seen from these data that it has only occurred to a very limited extent. The presence of a chromate conversion coating on the substrate bar appears to have reduced delamination by ≈50%, although it is difficult to quantify the true value due to the low amount of delamination occurring with both FBECR types. Also evident from the tables is the observation that, when compared with exposure to demineralised water, cyclic partial immersion of the concrete specimens in 3.5% NaCl solution increased the amount of delamination that took place.

Investigation of both the types of uncoated reinforcement bar in concrete specimens partially immersed in demineralised water revealed no visual evidence of corrosion. Both types of uncoated bar exposed to salt solution displayed visual evidence of extensive rusting, predominantly on their underside (Fig. 5(a)), whilst their topside was comparatively rust free. After rust removal

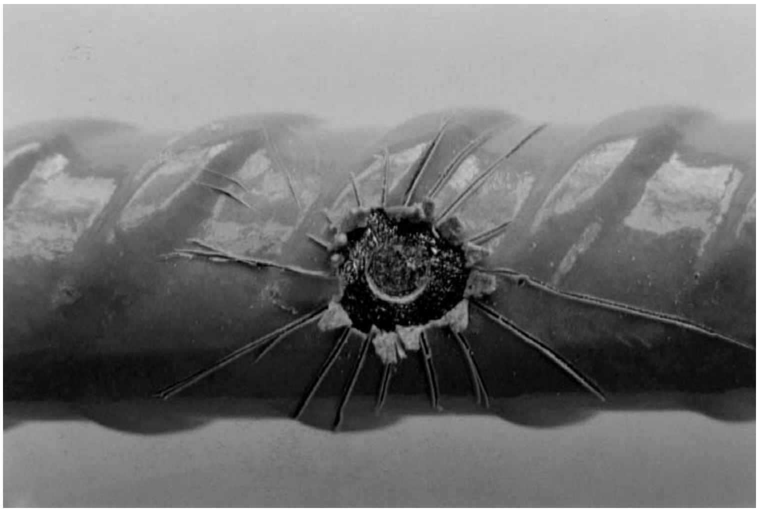

Fig. 4. Delamination of non-chromated FBECR after 1-year cyclic exposure in concrete to 3.5% NaCl solution.

Table 1
Extent of delamination of FBE from FBECR in concrete after 12-month test period

Rebar type	Radial delamination (mm)		
	Demineralised water	3.5% NaCl (aq)	3.5% NaCl (aq), no holiday
With chromate wash	0.5	1	None found
No chromate wash	0.8	1.8	None found

from these specimens for measurement of corrosion weight loss, it also became apparent that extensive pitting corrosion had taken place on both these types of reinforcement bar (Fig. 5(b)).

No weight loss was measurable on the uncoated bars exposed to demineralised water or the FBE-coated bars exposed to either test solution. There was however significant weight loss found on the uncoated bars cyclically exposed to salt solution (Table 2). The extent of weight loss does not appear to be affected by the presence of a chromate conversion coating, and produces a corrosion rate of ≈ 0.02–0.035 g/cm^2/yr. These values correspond with a general corrosion penetration rate of 0.025–0.045 mm/yr, with the assumption that the mild steel used had the same density as iron (7.86 g/cm^3).

These corrosion rates are $\approx$30–50% of corrosion rate data reported for unpainted mild steel in seawater (0.070 g/cm^2/yr) [19]. It should be noted that as the corrosion of the uncoated bars was localised in nature, local penetration rates will have been significantly higher. The extreme severity of the cyclic partial immersion testing conditions in terms of promotion of corrosion is therefore demonstrated, as is the effectiveness of the presence of an FBE coating on its prevention.

The similarity in corrosion performance between uncoated rebars irrespective of the presence of a chromate conversion coating when exposed to 3.5% NaCl solution indicates that the chromate treatment alone cannot retard the corrosion process. The difference in measured half-cell potentials between standard FBECR and that with a chromate wash suggest that in this system chromate does make a contribution to corrosion retardation in a concrete environment. It is however important to note that without the presence of a chromate wash, an FBE coating significantly retards bar corrosion when compared to that of uncoated bar.

The chromate conversion-coated FBECR concrete specimens placed in 3.5% NaCl solution tended not to reach potentials indicating corrosion (Fig. 3). When the concrete encapsulant was broken open at the end of testing, the exposed substrate steel of the FBECR at the holiday was bright and untarnished (Fig. 4). Subsequent investigation of weight loss (on scales accurate to 0.01 g) revealed that any that had taken place was too low to measure. These data suggest that the chromated FBECR tended to remain in a near-passive state. A possible contribution by the chromate conversion coating is noted in that the half-cell potentials of chromate-treated FBE-coated bars tended to remain more noble than those of the FBE-coated bars without chromate. The presence of the chromate conversion coating also affects delamination, reducing it by $\approx$50%, although as stated, because delamination of all the samples is so low, it is difficult to accurately quantify. Exposure of concrete FBECR-containing specimens to electrolyte containing NaCl also appears to increase extent of

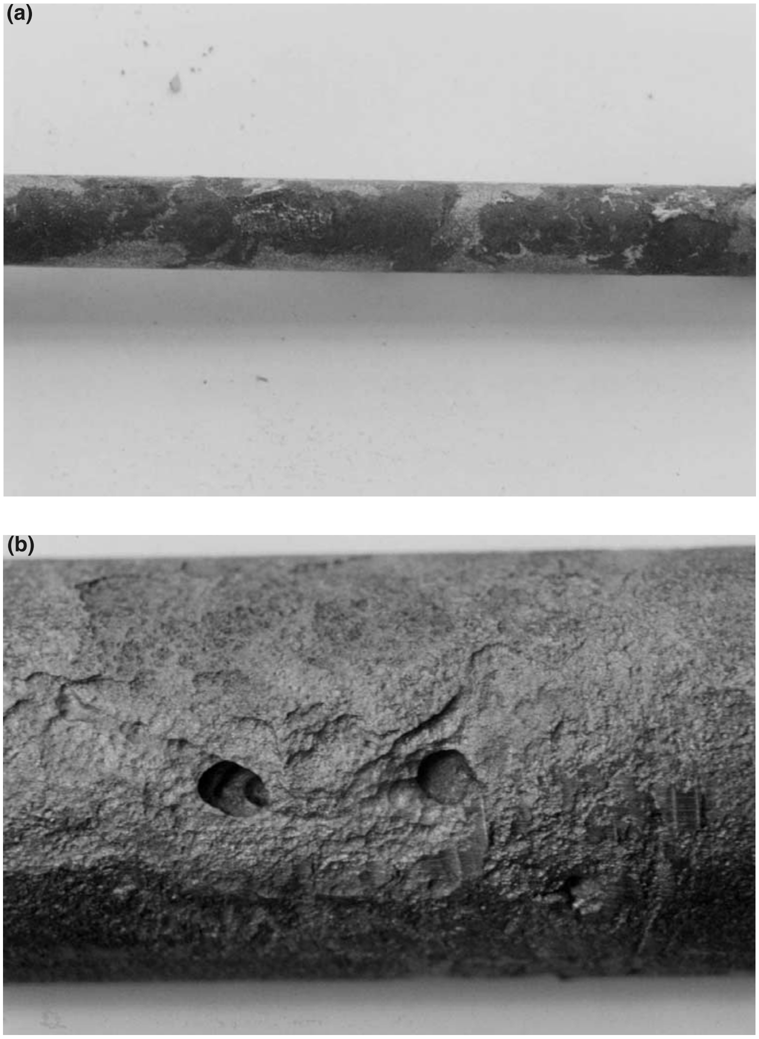

Fig. 5. (a) Underside of chromated rebar after 1-year cyclic exposure in concrete to 3.5% NaCl solution (b) pitting of rebar after 1-year cyclic exposure in concrete to 3.5% NaCl solution.

delamination, although an explanation for this cannot be derived from the above results.

It has been suggested that with the FBE-coated rebar acting as a cathode, anodic processes may be concentrated at a holiday in the coating, thus leading to excessive corrosion of the bar at this exposed area [20]. This suggestion relies on the assumption that for the cathodic process to take place underneath the FBE coating, current passage between anodic and cathodic areas is not greatly hindered. This ionic current must pass either through the coating or along the coating/substrate interface. The FBECR tested without holidays was shown to have a coating resistance of greater than 10^9 Ω cm^2, and as such would be a significant barrier to transport of ionic species through it. Physical delamination of the coating around a holiday was minimal after a year of accelerated testing in severe conditions, and so a large cathode to anode ratio is unlikely to be a major hazard in the early life of a concrete structure with FBE-coated bar. Allied to this is the lack of corrosion-related weight loss and any visual evidence that corrosion was occurring. Based on these findings, there is therefore little evidence that for the type of bar tested, accelerated localised corrosion at a holiday will take place.

Table 2
Average weight loss of uncoated bar in concrete after 12-month cyclic exposure to 3.5% NaCl solution

Rebar type	Weight loss (g in 1 yr)	Calculated corrosion rate ($g/cm^2/yr$)
Chromate wash	1.87	0.026
No chromate wash	1.61	0.022

Weight loss on all FBE-coated rebars was too small to be measurable. From analysis of potential/time data from the uncoated bars exposed to salt solution it may be surmised that chlorides reached the reinforcement bars within the first month of exposure because their potentials became more base than -350 mV. The non-chromated FBECR specimens also tended to achieve potentials more negative than -350 mV during their first month of partial immersion. Yet after a year of cyclic exposure to this environment, no corrosion was visible and delamination was reduced to 1 mm. Similar observations have been made by Yeomans [10] in his investigations of FBECRs in concrete. Both his and this work demonstrate that the use of half-cell potential alone, measured via a reference electrode external to the concrete under study, can generate data which may be subject to erroneous interpretation.

The nature of these results makes it difficult to determine with certainty whether the non-chromated FBECR specimens were passive or undergoing corrosion. What is clear is that the presence of the FBE coating has a significant effect on the limitation of any corrosion processes taking place.

4. Conclusions

Commercially produced FBE coatings on steel reinforcement bars were investigated in an environment of severely accelerated corrosivity such that their performance may be evaluated, and also their mechanisms of protection and failure found. The following conclusions are presented below:

1. In the conditions used, an FBE-coated reinforcement bar will significantly reduce the amount of corrosion that takes place when compared with uncoated reinforcement bar in the same environment.
2. The presence of a chromate conversion coating alone is unlikely to be sufficient to prevent corrosion of an uncoated reinforcement bar in chloride-contaminated concrete.
3. When the test specimens were placed in corrosive conditions far more severe than would be encountered by a concrete structure designed to the appropriate building standards, those with chromate conversion-coated FBECR did not corrode. Furthermore, no physical evidence that corrosion took place on the ordinary FBECR could be found.
4. Use of half-cell potential measurement to determine the activity of FBE-coated bar in concrete can lead to erroneous interpretation.

The nature of the damage to our FBE coating was a 3 mm diameter hole drilled through to the steel. It remains to be seen whether this kind of damage is representative or typical of the kind of damage a real coated rebar would receive in practice and further work is necessary to explore the validity of our findings to real systems.

References

[1] Weyers R, Cady P. Concr Int 1987;9:15.
[2] Clear KC. Concr Int 1992;14:58–64.
[3] Sagues A, Powers R. Effect of concrete environment on the corrosion performance of epoxy-coated reinforcing steel. Paper No. 311, Corrosion/89, NACE, Houston, 1989.
[4] Zayed A, Sagues A, Powers R. Corrosion of epoxy-coated reinforcing steel. Paper No. 379, Corrosion/89, NACE, Houston, 1989.
[5] Sagues A, Powers R, Zayed A. In: Page CL, editor. Corrosion of reinforcement in concrete. Amsterdam: Elsevier.
[6] Schiessl P, Reuter C. Transportation Research Circular No. 403, Transportation Research Board, NRC, March 1993.
[7] Treadaway KWJ, Davies H. Struct Eng 1989;67(6):99.
[8] Kobayashi K, Takewaka K. Int J Cem Comp Lwt Conc 1984;6(2):99.
[9] Clear KC, Virmani YP. Public Roads 1983;47(1):1.
[10] Yeomans SR. Corrosion 1994;50(1):72–81.
[11] Svensk Standard SIS 05 59 00, 1965.
[12] Darwin AB, Scantlebury JD. In: Scantlebury JD, Kendig MW, editors. Proceedings of the Symposium on Advances in Organic Coatings 2, vol. 95-13. The Electrochemical Society; 1995. p. 219–28.
[13] Darwin AB, Scantlebury JD. In: Cottis RA, editor. Proceedings of the Symposium on Advances in Organic Coatings 3, Paper 9. J Corr Sci Eng 1999 http://www.cp.umist.ac.uk/JCSE/.
[14] Teychenne DC, Franklin RE, Erntroy HC. Concrete Mixes, Department of Environment, HMSO, London, 1975.
[15] Page CL, Lambert P, Vassie PRW. Mater Struct 1991;24:243.
[16] BS8110: Part 1: 1985, Section 3, Table 3.2.
[17] Arvind Suryavanshi. PhD Thesis, UMIST, 1994.
[18] ASTM C876-91, ASTM, 1999.
[19] Mayne JEO. JOCCA 1949;32:352.
[20] Pfeifer DW, Landgren R, Krauss P. Transportation Research Circular No. 403, National Research Council, Washington DC, USA, March 1993.