Optimization of a Commercial Brake Pad Formulation

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ABSTRACT: A brake pad material used in a popular, commercially available vehicle that consisted of steel wool, iron powder, graphite, coke, styrene–butadiene rubber, MgO, $BaSO_4$, and phenolic resin was tested with the friction assessment and screening test. The average friction coefficient (0.357) and total wear (19.75 wt %) were measured. An alternative friction material formulated with identical constituents but optimized with the golden section principle and relational grade analysis was produced in a laboratory environment. This material exhibited an average friction coefficient of 0.419 and a low total wear of 6.25 wt %. An analysis of component costs indicated that the large volume price of the commercial material, $1.01/kg, was less than that of the laboratory material, $1.21/kg. However, the performance/cost ratio of the new material was appreciably greater. © 2002 Wiley Periodicals, Inc. J Appl Polym Sci 84: 2498–2504, 2002

Key words: friction materials; optimization; design of experiments; golden section; relational grade analysis; composites; fillers; thermosets

INTRODUCTION

The first friction material (1878–1897) was based on hair or cotton.[1–3] As a matter of fact, automotive friction materials have been formulated for about 100 years. In the early 1920s, asbestos fiber was chosen as a friction material for automobiles, trucks, and all kinds of moving machinery. Because asbestos can cause health problems, brake-lining designers have been scrambling to find a replacement for it, using glass fibers, mineral fibers, metal fibers, and, more recently, carbon and synthetic fibers. Mixtures of chopped or powdered metal and other filler materials bound together with phenolic resin, known as semimetallic brake pads, have been popular since the 1970s.[4,5] Metal is mostly favored for heat transfer. Generally, steel wool and iron powder can be used for higher temperature applications. Thirty years ago, when disc brakes were becoming common, the brake users were impressed by how long the linings could last. Unfortunately, most of the late model brake pads wore quickly. Therefore, the tendency is to design new friction materials with good wear resistance.[6] Furthermore, most of the cars today are designed for more horsepower, which makes them more likely to reach a higher speed. As a result, manufacturers are investing heavily in new friction materials to get optimal performance from the brake pads. Good performance for brake pads is not the only concern for engineers designing them; the costs of their manufacturing and raw materials have to be taken into consideration.

Until now, however, many of the brake pads available in the market did not have good performance, causing the need for frequent replacement of the brake pads. Brake pads with good performance will save customers money. For further brake design, the main consideration in the de-

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Table I Composition and Friction Performance of CFE and Cost of Raw Materials

	CFE	Cost, \$/kg
Steel wool	0.25	1.18
Iron powder	0.07	1.02
Graphite	0.05	1.48
Coke	0.05	0.87
SBR	0.05	1.44
MgO	0.04	1.18
$BaSO_4$	0.18	0.20
Phenolic	0.31	1.44
Average μ	0.357	
Wear (wt %)	19.75	
Formula cost (\$/kg)	1.01	

velopment of brake pads is what kinds of materials to use and the percentage amount of the materials to mix to extend the life of the brake pads. Because the development of friction materials is a complex and interactive process, most formulations that are available in the market were designed by trial and error coupled with prior experience and testing expertise called one-variable-at-a-time experimentation (OVAT design).[7] Recently, multiple regression analysis coupled with genetic algorithms,[8] chemometrics,[9] and Taguchi design[10] was developed for the optimization of friction formulations. However, these methods require a great deal of data with heavy-duty computation to draw conclusions with reasonable confidence. The interaction effects among the multiple components of friction performance are especially difficult to statistically analyze.

A commercial brake pad formulation (CFE) analyzed and supplied by Dr. Peter Filip at the Center for Advanced Friction Studies and the results of the friction coefficient (μ) and wear of a specimen prepared according to the CFE formulation tested with the friction assessment and screening test (FAST) are shown in Table I. The average μ value of the brake pads used in North America is around 0.35–0.45; that of pads used in Europe and Asia is higher than 0.45.[11] It has been proven that the μ value of CFE is available in North America because the average value of μ is 0.357, but the wear is too high (W = 19.75 wt %) and needs to be minimized. In this work, an optimizing formulation technique[12,13] based on the golden section principle[14,15] in combination with relational grade analysis[16,17] was used to develop a friction material of high performance from routine components. Essentially, a commercial brake material was chemically analyzed, and the volume fraction of its component phases was determined. These components were then reformulated to produce a new friction material of superior performance as measured by FAST.

EXPERIMENTAL

Raw Materials Used and Preparation of Friction Materials

All raw materials except phenolic resin were mixed in a high-speed blender for 40 s. Then, phenolic resin was mixed with those ingredients for 30 s. The mixture was molded with a hot press at 177°C for 50 min. The samples were cured at 120°C for 60 min, at 140°C for 60 min, and at 170°C for 120 min.

FAST

μ and wear were measured with FAST (M100, Link Engineering Co., Plymouth, MI). FAST consists of a flat plate of cast iron with a diameter of 180 mm and a thickness of 38 mm rotating at a speed of 6.96 m/s, which is appropriate for a disc in the braking system of an automobile moving at 50 km/h.[18] A small specimen (13.5 mm × 12.7 mm × 4.7 mm) suspended from a hinged arm is pulled onto the surface of the disc with a normal force of appropriate magnitude. The testing system is controlled by a hydraulic feedback system that continuously changes the normal force to maintain a constant friction force of 17.4 N.[19] The mean temperature measured at some point on the rubbing track increases with time at a rate that is independent of the composition of the friction material. FAST is a drag test 90 min in duration. All tests were carried out in ambient air. μ was recorded every 5 s. The wear was expressed as $W = (W_0 - W_1)/W_0 \times 100\%$, where W_0 and W_1 are the weights of the specimen before and after FAST, respectively.

RESULTS AND DISCUSSION

Optimization of CFE Formulation

Phase 1

A schematic of the optimization formulation technique is shown in Figure 1. The golden section principle is based on the most mystical way to

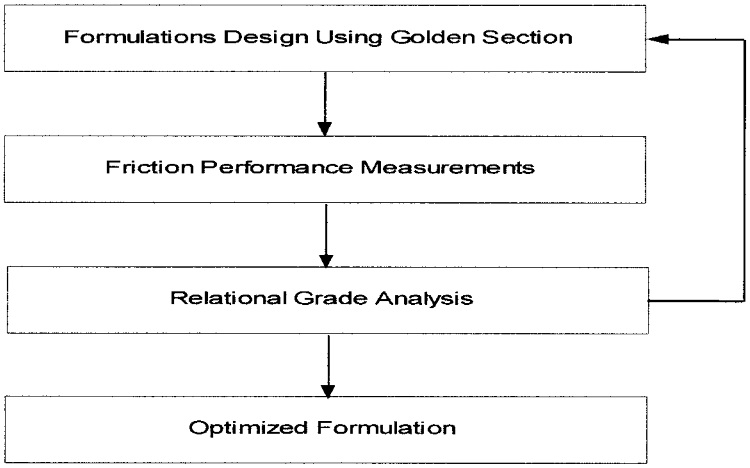

Figure 1 Optimization formulation technique.

divide a whole into a large piece and a small piece. As an optimization technique, it assumes that one minimum or maximum in a measured property exists between two points (in two-component systems). This technique is a relatively efficient method for reducing the error band connected with the position of the assumed point. For example, if the point exists somewhere between *A* and *B* and the distance between them is one unit, then the position can be more accurately defined if two measurements of the property of interest are made, one at a point 0.618 units from point *A* (0.382 units from *B*) and another 0.618 units from *B* (0.382 units from *A*). Depending on which measurement is larger, the position of the maximum can be established with error limits reduced from 1 to 0.618. It turns out that one of the first two measurements also falls at a distance of 0.618 new units from one of the new limits. The maximum is now defined within smaller limits, a distance of 0.618^2 along the original axis. These limits become progressively smaller according to the expression 0.618^{n-1}, where n is the number of measurements made.

For the amount of the raw materials to be mixed, an approach was initially designed to optimize new formulations based on the golden section, in which the volume fraction of the metal group (V_m) and volume fraction of the nonmetal group (V_{nm}) were equal to 0.382 and the volume fraction of the binder (V_b) was equal to 0.236. These designations agreed with 0.618^n, where $n = 2$ or 3.

The raw materials used in optimized formulations (FE) can be classified into three groups: metal (steel wool and iron powder), nonmetal [graphite, coke, styrene–butadiene rubber (SBR), MgO, and $BaSO_4$], and binder (phenolic resin). Each ingredient plays a role in improving friction performance, depending on its content. Steel wool is a reinforcement. Graphite and coke are used as solid lubricants. SBR is used as a toughening agent for the binder. MgO is used for promoting curing of the binder, and $BaSO_4$ and iron powder are cheap fillers. The golden section was used to determine the volume fraction of each component. Ten formulations with different volume fractions were designed with 0.618^n, where $n = 3, 4, 5, \ldots$, as phase 1 for FAST, and the values of μ and wear loss of these formulations are shown in Table II.

Iron powder was used as the main metal filler in the formulations FE-1 to FE-4, and steel wool was used as the main reinforcement in FE-5 to FE-10. In a comparison of the wear and average μ values of the two different main components, we found that better wear resulted and higher μ values were obtained with the formulations that used steel wool as the main reinforcement because the steel wool had a reinforcement effect in the friction materials. The formulation FE-4 contained 0.146 of graphite and 0.090 of coke, which acted as lubricating agents and provided better wear resistance in the formulations in which iron powder was the main metal filler. According to the friction performance of the ten formulations, FE-7 had a lower wear loss of 8.33 wt % and an average μ value of 0.429. It was used for further optimization.

In the formulation design, it is important to know which ingredient has the greatest effect on friction performance. Relational grade analysis can be used to determine the sensitivity of the

Table II Formulations Designed with 0.618^n (Phase 1)

	FE-1	FE-2	FE-3	FE-4	FE-5	FE-6	FE-7	FE-8	FE-9	FE-10
Steel wool	0.146	0.146	0.146	0.146	0.236	0.236	0.236	0.236	0.236	0.236
Iron powder	0.236	0.236	0.236	0.236	0.146	0.146	0.146	0.146	0.146	0.146
Graphite	0.090	0.022	0.022	0.146	0.034	0.013	0.236	0.022	0.146	0.056
Coke	0.013	0.034	0.090	0.090	0.056	0.090	0.022	0.236	0.034	0.090
SBR	0.022	0.056	0.034	0.022	0.056	0.022	0.090	0.034	0.022	0.034
MgO	0.021	0.236	0.090	0.090	0.090	0.021	0.021	0.056	0.090	0.146
$BaSO_4$	0.236	0.034	0.146	0.034	0.146	0.236	0.013	0.034	0.090	0.056
Phenolic	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236	0.236
Average μ	0.313	0.331	0.327	0.319	0.344	0.359	0.429	0.332	0.374	0.339
Wear (wt %)	44.42	59.93	37.37	15.98	24.22	20.33	8.33	13.39	22.87	17.07
Formula cost ($/kg)	0.94	1.10	0.99	1.11	1.03	0.94	1.18	1.09	1.09	1.10

measurement to changes in the volume fraction of each phase of a multiphase system. Essentially, changes in many constituents are made, and the resulting change in the property is measured. A number of experiments are carried out, and the resulting percentage change in the measured property is compared to the percentage change in the volume fraction of each component that caused it. If a statistically large number of tests are performed, the sensitivity of the property to each constituent can be estimated.

The relational grade (γ_i) can be calculated with the following formulas:

$$\xi_i(k) = \frac{\min\min|y_i(k) - x_i(k)| + 0.5\max\max|y_i(k) - x_i(k)|}{|y_i(k) - x_i(k)| + 0.5\max\max|y_i(k) - x_i(k)|} \tag{1}$$

$$\gamma_i = \frac{1}{n}\sum \xi(k) \tag{2}$$

where $\xi_i(k)$ is the relational coefficient, $y_i(k)$ is the normalized friction performance matrix, $x_i(k)$ is the normalized composition matrix, min represents the minimum, and max means the maximum.

The relational grades of seven ingredients calculated with eqs. (1) and (2) are ranked as follows:

$$\underset{0.9734}{\text{Iron powder}} < \underset{0.9704}{\text{BaSO}_4} < \underset{0.9293}{\text{Graphite}} < \underset{0.9158}{\text{Steel Wool}} < \underset{0.8908}{\text{SBR}} < \underset{0.7524}{\text{MgO}} < \underset{0.6905}{\text{Coke for wear}} \tag{3}$$

$$\underset{0.9698}{\text{Steel wool}} > \underset{0.9629}{\text{Iron powder}} > \underset{0.9285}{\text{BaSO}_4} > \underset{0.9265}{\text{Graphite}} > \underset{0.9263}{\text{SBR}} > \underset{0.7743}{\text{MgO}} > \underset{0.7102}{\text{Coke for friction coefficient}} \tag{4}$$

The ingredient in the left rank (large relational grade) has more sensitivity than the ingredient in the right side (smaller relational grade). For instance, coke, MgO, and SBR have positive effects on reducing wear but poor effects on enhancing μ, and steel wool and iron powder have positive effects on enhancing μ, but iron powder has a poor effect on reducing wear. The rank for wear is consistent with our ternary (ABC systems, where A is steel wool, B is an organic binder, and C is a third ingredient) combinatorial screening of raw materials for semimetallic friction materials in which combinations of coke, MgO, SBR, graphite, and steel wool show good wear resistance.[20] We found that the wear of friction materials could be reduced through a reinforcing mechanism (the addition of fiber reinforcements, e.g., steel wool and aramid pulp), a toughening mechanism (the addition of rubbers, e.g., SBR and nitrile rubber), a lubrication mechanism (the addition of lubricants, e.g., coke and graphite), and an abrasion mechanism (the addition of abrasives, e.g., alumina).[21] Because the basic requirements for friction materials are stable and high values of μ and lower wear, the amount of the ingredient with the larger relational grade for μ should be increased, and the amount of the ingredient with the larger relational grade for wear should be decreased. Instead of the material with the greatest effect on μ and the least effect on wear loss, the volume

Table III Formulations Designed According to Relational Grade Analysis (Phase 1)

	FE-11	FE-12	FE-13	FE-14
Steel wool	0.292	0.326	0.416	0.472
Iron powder	0.090	0.056	0.056	0.056
Graphite	0.236	0.236	0.146	0.090
Coke	0.022	0.022	0.022	0.022
SBR	0.090	0.090	0.090	0.090
MgO	0.021	0.021	0.021	0.021
$BaSO_4$	0.013	0.013	0.013	0.013
Phenolic	0.236	0.236	0.236	0.236
Average μ	0.467	0.413	0.394	0.410
Wear (wt %)	7.79	7.70	8.03	9.64
Formula cost ($/kg)	1.20	1.21	1.19	1.19

fraction of steel wool should be increased, and the volume fraction of iron powder, $BaSO_4$, and graphite should be decreased according to the ranks (3) and (4). Because the amount of $BaSO_4$ in FE-7 is too small (0.013) to change, decreasing its volume fraction could be eliminated. On the basis of FE-7, with steel wool as the main reinforcement, FE-11 and FE-12 were calculated with the volume fraction of steel wool increasing and the volume fraction of iron powder instantaneously decreasing by 0.056 and 0.090, respectively. Then, FE-13 and FE-14 were calculated with the volume fraction of steel wool increasing and the volume fraction of graphite instantaneously decreasing by 0.090 and 0.146, respectively, on the basis of FE-12. These formulations were calculated by $0.618^n \pm 0.618^m$, where $0.618^n = 0.236, 0.146, 0.090, \ldots$ when $n = 3, 4, 5, \ldots$ and $0.618^m = 0.146, 0.090, 0.056 \ldots$ when $m = 4, 5, 6, \ldots$. According to the relational grade of each ingredient, the volume fraction changes of four formulations (FE-11 to FE-14) and their friction performances are shown in Table III. By comparing the results before and after relational grade analysis, we found better friction performance in FE-12 with an average μ value of 0.413 and lower wear loss of 7.70 wt %. From this point of view, relational grade analysis is an effective way of obtaining better friction performance.

Phase 2

The effect of the changes in the volume fraction between metal and nonmetal groups on friction performance was detected in phase 2. On the basis of FE-12, FE-15 and FE-16 were calculated with V_m increasing and V_{nm} instantaneously decreasing by 0.056 and 0.09, respectively. These formulations were also calculated by $0.618^n \pm 0.618^m$. The volume fraction of each group in FE-12 was expressed by 0.618^n, and the volume fraction of each group in FE-15 to FE-18 was expressed by $0.618^n \pm 0.618^m$. For example, V_m in FE-12 is 0.382 (0.618^2) and in FE-15 is $0.382 + 0.056$ (0.618^6) $= 0.438$. V_{nm} in FE-12 is 0.382 and in FE-15 is $0.382 - 0.056 = 0.326$. The volume fraction of each ingredient in their group was proportionally varied. For example, the volume fraction of steel wool in FE-15 was calculated by $0.326 + 0.326 \times 0.056/0.382 = 0.374$, and the volume fraction of graphite in FE-15 was calculated by $0.236 - 0.236 \times 0.056/0.382 = 0.201$. However, FE-17 and FE-18 were calculated by V_m decreasing and V_{nm} instantaneously increasing by 0.056 and 0.09, respectively, on the basis of FE-12. The compositions and friction performances of FE-15 to FE-18 are shown in Table IV. Comparing the results of FE-12 with those of FE-15 to FE-18, we obtained better friction performance in FE-17, where $V_m = 0.326$ and $V_{nm} = 0.438$ with an average μ value of 0.365 and a wear loss of 6.36 wt %. This indicated that the amount of nonmetal groups is larger than that of metal groups for good friction performance. μ of FE-17 is similar to that of the commercial formulation CFE, but the wear of FE-17 is lower than that of CFE.

Phase 3

In phase 3, the effect of changes in the volume fraction between the binder group and metal and nonmetal groups was tested. FE-19, FE-20, and FE-21 were calculated with V_b decreasing and V_m

Table IV Formulations Designed for Changing V_m and V_{nm} (Phase 2)

	FE-15	FE-16	FE-17	FE-18
Steel wool	0.374	0.403	0.278	0.249
Iron powder	0.064	0.069	0.048	0.043
Graphite	0.201	0.180	0.271	0.292
Coke	0.019	0.017	0.025	0.027
SBR	0.077	0.069	0.103	0.111
MgO	0.018	0.016	0.024	0.026
$BaSO_4$	0.011	0.010	0.015	0.016
Phenolic	0.236	0.236	0.236	0.236
Average μ	0.399	0.365	0.365	0.351
Wear (wt %)	8.51	9.41	6.36	6.75
Formula cost ($/kg)	1.20	1.20	1.22	1.23

Table V Formulations Designed for Changing V_b (Phase 3)

	FE-19	FE-20	FE-21	FE-22	FE-23
Steel wool	0.290	0.299	0.311	0.266	0.257
Iron powder	0.050	0.051	0.053	0.046	0.044
Graphite	0.283	0.291	0.303	0.259	0.251
Coke	0.026	0.027	0.028	0.024	0.025
SBR	0.108	0.110	0.115	0.098	0.095
MgO	0.025	0.026	0.027	0.023	0.022
$BaSO_4$	0.016	0.016	0.017	0.014	0.014
Phenolic	0.202	0.180	0.146	0.270	0.292
Average μ	0.422	0.419	0.423	0.427	0.403
Wear (wt %)	6.84	6.25	6.71	9.08	6.62
Formula cost ($/kg)	1.22	1.21	1.21	1.22	1.23

$+ V_{nm}$ instantaneously increasing by 0.034, 0.056, and 0.090, respectively, on the basis of FE-17. However, FE-22 and FE-23 were calculated with V_b increasing and $V_m + V_{nm}$ instantaneously decreasing by 0.034 and 0.056, respectively, on the basis of FE-17. The calculations were the same as those for phase 2. The results of μ and wear loss for each formulation are shown in Table V. The best friction performance was obtained for FE-20, where $V_b = 0.180$, $V_m = 0.350$, and $V_{nm} = 0.470$ with an average μ value of 0.420 and a lowest wear loss of 6.25 wt %. According to the relations between the changes in the amounts of the binder group and metal and nonmetal groups, the role of the binder is mainly to bind all metal and nonmetal ingredients together. A theoretical analysis of particle packing models shows that there is a critical volume fraction of the binder ($V_{b,cr}$).[21] The binder amount needs to be larger than $V_{b,cr}$. The FAST curves of the optimized formulation FE-20 and the commercial formulation CFE are compared in Figure 2. The friction performance of FE-20 is better than that of CFE.

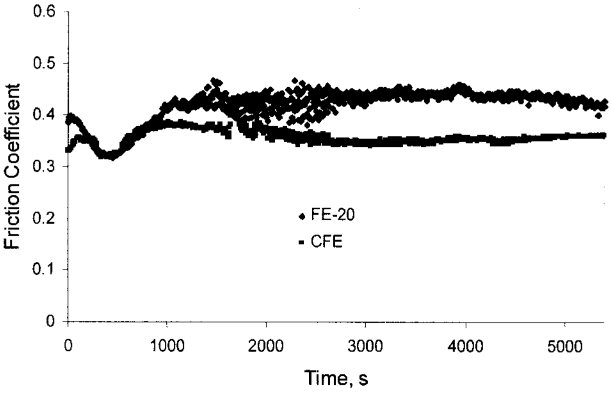

Figure 2 FAST curves of FE-20 and CFE.

Economic Considerations

When a new brake pad material is being made, the main factors to consider are not only a moderate value of μ and a low wear rate but also low costs of both the raw materials used and the manufacturing process. In general, the cost of a new material with high performance is higher than the cost of an old one. The performance/cost ratio is a comprehensive factor to consider for the use of a new material. The formula cost of the original commercial brake pad formulation (CFE) is \$1.01/kg, FE-17 with the same level of μ as CFE has is \$1.22/kg, and the optimized formulation FE-20 is \$1.21/kg, as shown in Tables I, IV, and V, respectively. Although the cost of FE-17 and FE-20 is 0.20 times greater than that of CFE, the wear resistance of FE-17 and FE-20 is 2.16 times greater than that of CFE. The performance/cost ratio of FE-17 and FE-20 is much higher than that of CFE.

CONCLUSIONS

The friction performance of the commercial brake pad formulation (CFE) is not optimized for greatest wear. With an optimization formulation technique based on the golden section principle coupled with relational grade analysis, the wear rate of CFE was successfully minimized. The formulation FE-17 of phase 2 has an average μ value of 0.365, which is similar to that of CFE (average $\mu = 0.357$), as required for North America's friction formulations, but the wear rate ($W = 6.36\%$) is lower than that of CFE ($W = 19.75\%$). The optimized formulation FE-20 has an average μ value of 0.419, which is higher than that of CFE, and the wear of FE-20 ($W = 6.25\%$) is appreciably lower than that of CFE. According to the friction performance and formula cost of CFE and FE-20 (or FE-17), doubling the lifetime only slightly increases the formula cost.

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