



**A VALUE-FOCUSED THINKING MODEL
FOR THE SELECTION OF THE BEST RIGID
PAVEMENT PARTIAL-DEPTH SPALL
REPAIR MATERIAL**

THESIS

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Abstract

Concrete spalls on airfield pavements generate foreign object debris (FOD) that is damaging to aircraft engines, and may damage landing gear by roughening the pavement surface. Repairing spalled concrete on aging and deteriorating airfields is essential for its safe operational use. Picking the best repair material from many products on the commercial market is difficult. There is wide variation on material properties, and good performance on certain criteria is critical to constructing long lasting repairs.

Since there is currently no procedure for Air Force decision-makers to select the best rigid-pavement repair material, a model was created using Value-Focused Thinking (VFT) to evaluate repair material alternatives. Fourteen products were compared against each other. Each was scored using fourteen evaluation measures that were identified as important to the repair material selection process. Pavemend EX-H was found to be the best choice for repairs conducted during conventional, steady-state operations. Pavemend VR was found to be the best option for repairs that must be ready for traffic within hours after placement, such as during contingency operations. VFT was shown to be an effective methodology for objectively ranking repair products, while providing a systematic process that can be tailored for future circumstance

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A VALUE-FOCUSED THINKING MODEL FOR THE SELECTION OF THE BEST RIGID PAVEMENT, PARTIAL-DEPTH SPALL REPAIR MATERIAL

I. Introduction

1.1 Overview

Portland Cement Concrete (PCC) is the most common pavement surface used in airfield runways, taxiways and parking aprons. When properly designed, constructed, and maintained, it provides a smooth surface capable of supporting the loads and tire pressures of all types of aircraft. However, PCC pavements that have outlived their useful lives or that have not been maintained may develop cracks and spalls that are damaging to the pavement surface. A spall is a pavement distress in the form of a crack, often along pavement joints and edges. Figure 1 shows typical spalls in concrete pavement. Spalls are commonly partial depth, but may be full depth, in which case the structural capacity of the slab is weakened. Repairing spalls as they occur is important for maintaining the health of airfield pavements, and is essential to the safety of aircraft as they take off, land, and taxi. Engineers from all branches of service perform these repairs, to include Air Force Civil Engineers, Navy Seabees, and Army Combat Engineers.

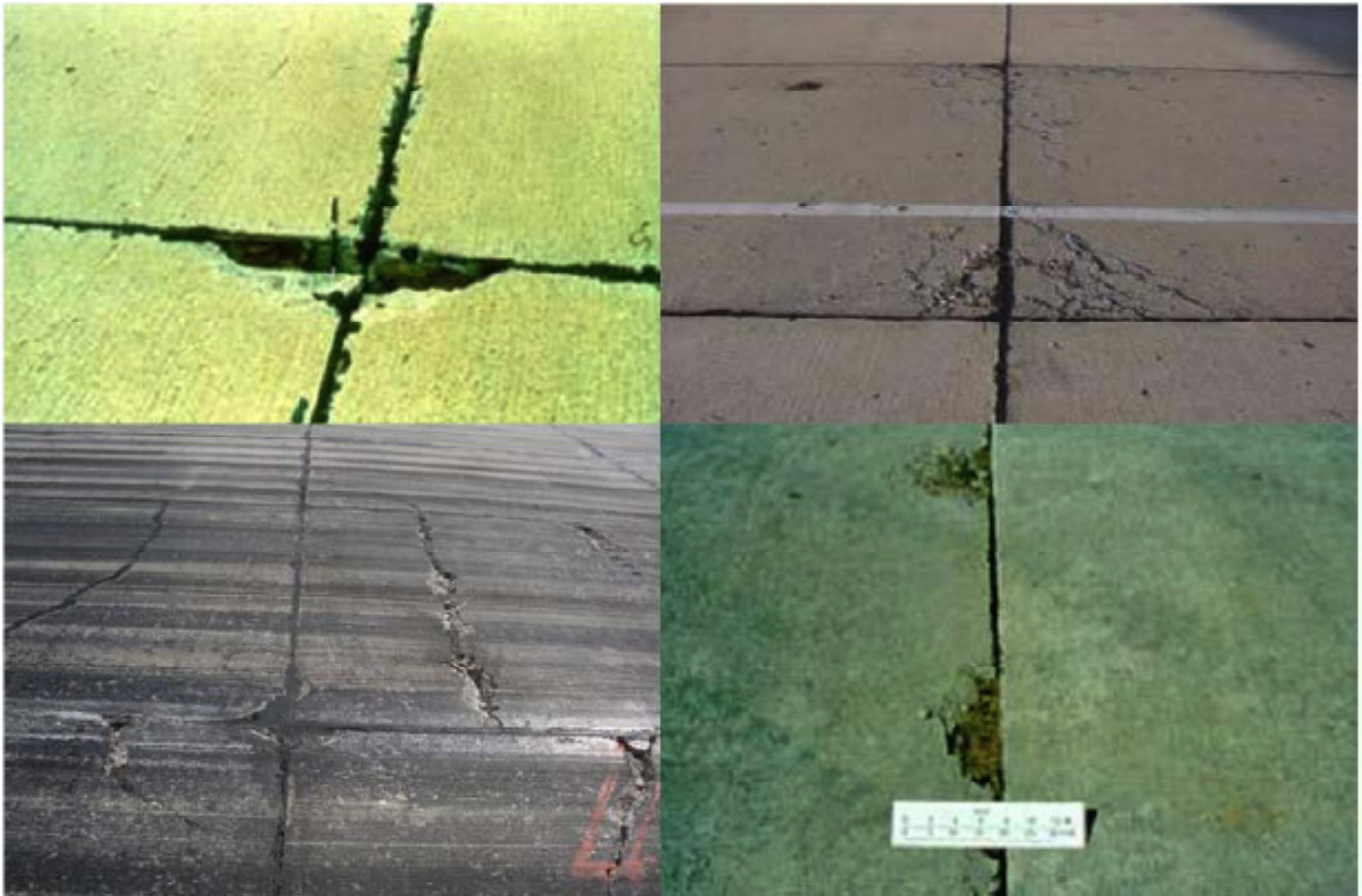


Figure 1. Concrete Pavement Spalls

Military engineers need a decision tool to identify which repair materials are ideal candidates for spall repairs of airfield pavements. Their decision could depend on local factors and conditions for a particular airfield. The biggest threat spalls pose is in the form of Foreign Object Debris (FOD). Loose concrete chips and aggregates from a concrete spall have the potential to be sucked into jet engines, or damage propellers and rotors of million dollar aircraft. Spalls also increase the roughness of the pavement, possibly to the point that the pavement becomes damaging to the landing gear of fighter aircraft. Sharp edges from spalling concrete also have the potential to cut aircraft tires.

3.6.1 Cost Value Functions

The first cost measure, cost per yield, is a measure of the cost of a material for a given yield. The units chosen for this measure are US dollars per cubic foot of material.

This function is continuous because cost can take on an infinite number of values. It is monotonically decreasing since high cost is not preferable. The decision makers chose a lower bound of \$1 per cubic foot, and an upper bound of \$200 per cubic foot of material. Figure 19 shows the Cost per Yield SDVF.

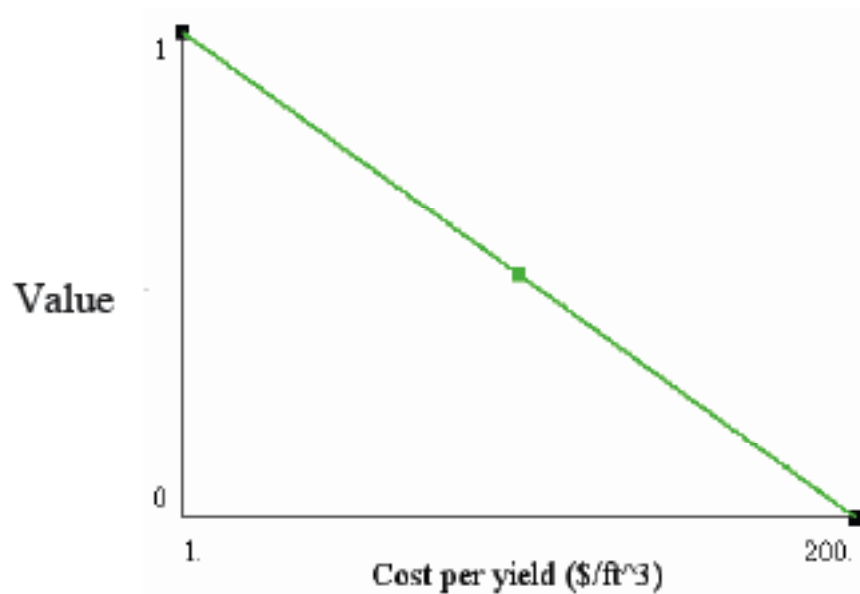


Figure 19. Cost per Yield SDVF

The second measure specifies whether a repair material requires a specialized aggregate. This SDVF is categorical since the range of possibilities is binary. A repair material that does not require specialized aggregates receives the full score of one on this measure. Figure 20 shows the categorical SDVF.

Category	Value
Yes	0.000
No	1.000



Figure 20. Requires Specialized Aggregates SDVF

Figure 20. Requires Specialized Aggregates SDVF

3.6.2 Desirable Material Properties Value Functions

The ASTM C 882 slant shear bond test measures a repair materials ability to resist sliding between a material and the concrete substrate. The units for this measure are pounds per square inch (PSI). The decision makers chose a continuous, linear function with an upper bound of 3000 PSI and lower bound of 1500 PSI. The function is increasing since higher bond strengths are preferred. Figure 21 shows the ASTM C 882 SDVF.

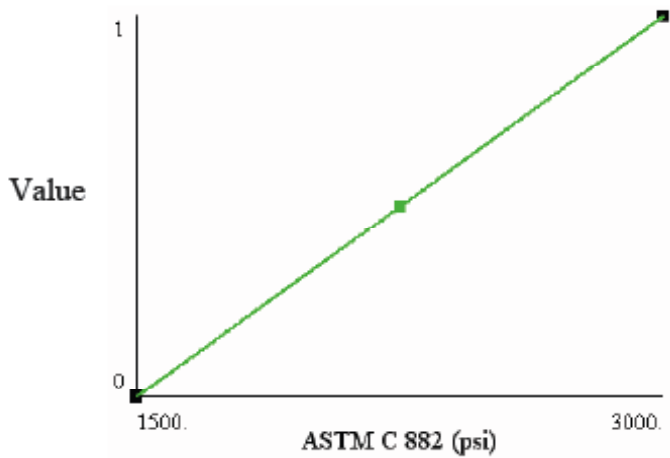


Figure 21. ASTM C 882 SDVF

ASTM C 39 measures the compressive strength of a material specimen. This test represents the strength of a material after 28 days of curing. The units for this measure are PSI. The decision makers chose a linear, continuous function with an upper bound of 10000 PSI and a lower bound of 2500 PSI. The function is increasing since higher compressive strengths are preferred. Figure 22 shows the ASTM C 39 SDVF.

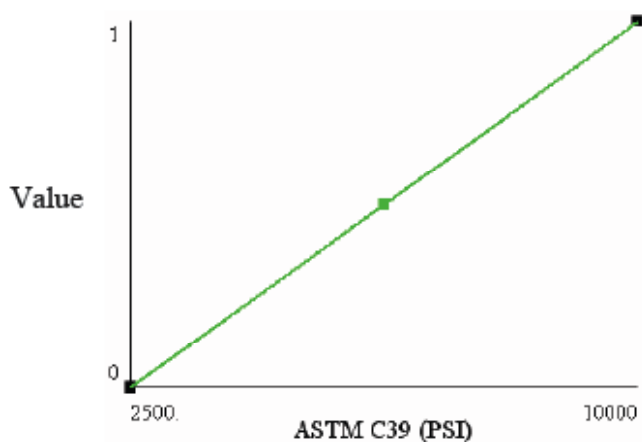


Figure 22. ASTM C 39 SDVF

ASTM C 666 is a standard test to determine the durability of a material when subjected to freeze/thaw cycles. To begin the test, a material's dynamic modulus of elasticity is first measured. Next, the material is subjected to 300 freezing and thawing cycles. After the test, the change in the materials dynamic modulus of elasticity is recorded. The unit for this measure is the percentage of dynamic modulus retained after the test. This test uses a continuous function since there is an infinite range of values for percent dynamic modulus retained. The function is increasing since higher percentages of dynamic modulus retained represent more durable materials. The decision makers chose an upper bound of 80% and a lower bound of 0%. Figure 23 shows the ASTM C 666 SDVF.

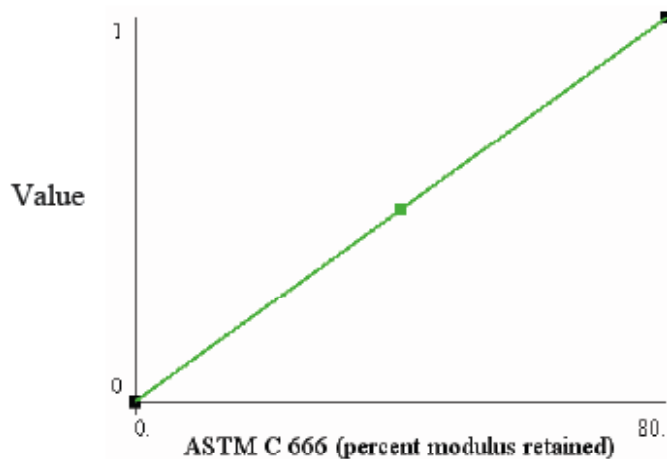
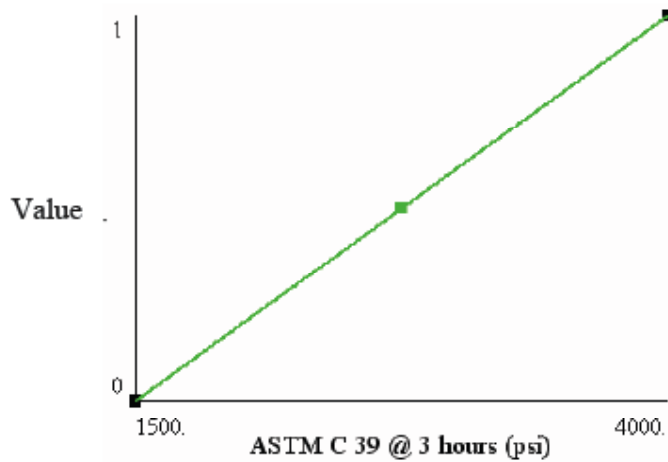


Figure 23. ASTM C 666 SDVF

Early strength is measured by the same test as compressive strength (ASTM C 39); To measure early strength however, this test is performed after three hours of curing instead of 28 days. The units for this test are PSI, and the function is continuous since the range of possible values is infinite. The function is increasing since high early strength is preferred. The decision

makers chose an upper bound of 4000 PSI, and a lower bound of 1500 PSI. Figure 24 shows the SDVF for early strength.



SDVF for Early Strength (ASTM C 39 after 3 hours of curing)

Modulus of elasticity is measured by ASTM C 469. This test measures the slope of a material's stress/strain curve when deformed, or in simpler terms, the stiffness of a material. The units for this test are PSI. The decision makers felt that an ideal material would have a modulus of elasticity equal to that of the concrete substrate. The levels of modulus of elasticity for alternatives will therefore be inputted in this model as the deviation, or delta from an assumed value of concrete pavement. The decision makers chose 4.5 million PSI as a typical value for concrete pavement. The value function for this measure will scale the modulus differential that deviates from 4.5 million PSI. The function is continuous since there is an infinite range of possible deviation values. The decision makers chose an upper bound of 4.5 million PSI, and a lower bound of 0 PSI (no differential from substrate). The function is decreasing because a high modulus differential from the existing substrate is not preferred. Figure 25 shows the SDVF for modulus of elasticity differential.

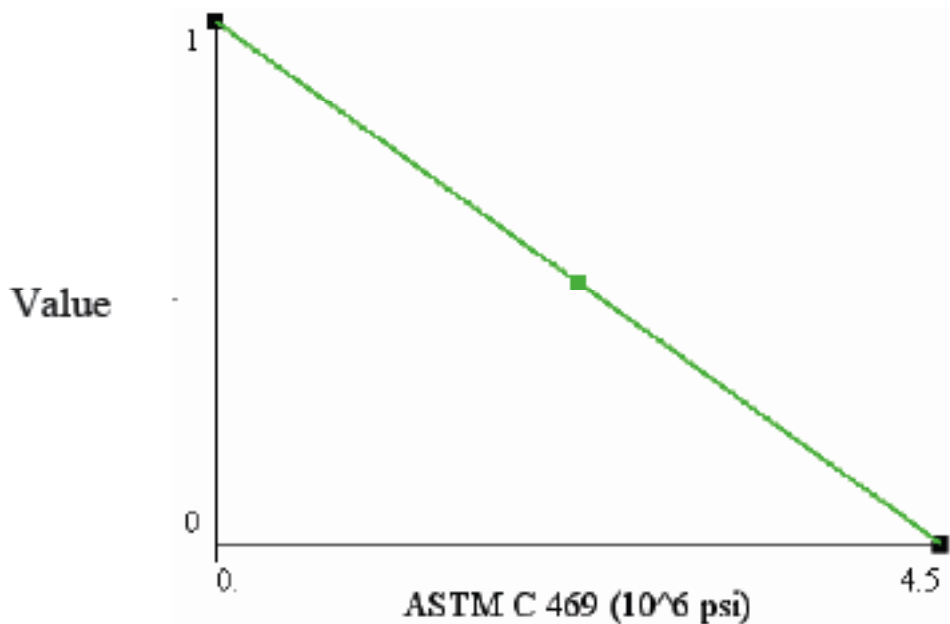


Figure 25. Modulus of Elasticity Differential from Substrate SDVF

Restrained drying shrinkage is a measure of the shrinkage a material will undergo while under restrained (confined) conditions. High shrinkage materials are avoided because of the potential for cracking while in the curing phase. A material's cement type was chosen as a proxy measure for this value. In general, materials that include calcium aluminate (C3A) or silica fume (SiO₂) as mineral components experience high shrinkage (Holt, 2001:175). Materials with magnesium phosphate as their primary cement component have low shrinkage. Materials with Portland cement as their primary cement component will be classified as medium shrinkage. The value function for this measure is categorical, with possible value of low, medium, and high. The function is decreasing since high shrinkage is not preferred. Figure 26 shows the categorical SDVF for restrained shrinkage.

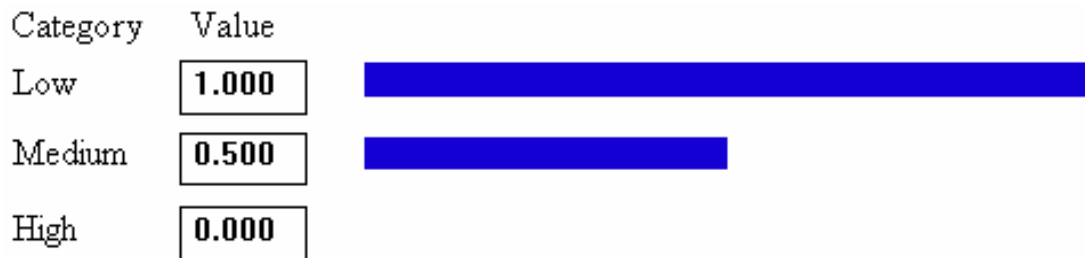


Figure 26. Restrained Shrinkage SDVF

ASTM C 531 measures a material’s coefficient of thermal expansion. The coefficient of thermal expansion is the rate at which a material expands or contracts to changes in temperature. The units for this test are microstrains per degree Fahrenheit. A microstrain is the length in millionths of an inch that a material will shrink or swell per each inch of length. The decision makers felt that an ideal material would have a coefficient of thermal expansion similar to that of the concrete substrate. Any differential between the two can cause movement fluctuations, and negatively affect the performance of the repair (ACI, 2006:6). The typical range of values for thermal coefficients of portland cement concrete is typically 2 to 8 microstrains/° F (ACI, 2006:7). The decision makers chose 5 microstrains/°F as an assumed value for concrete pavements. Therefore, the deviations from this value will be scaled using a continuous SDVF. The decision makers chose an upper bound of 5 microstrains/°F and a lower bound of 0 microstrains/°F (no differential). The function is decreasing since high thermal coefficient deviations are not preferred. Figure 27 shows the SDVF for thermal coefficient deviation.

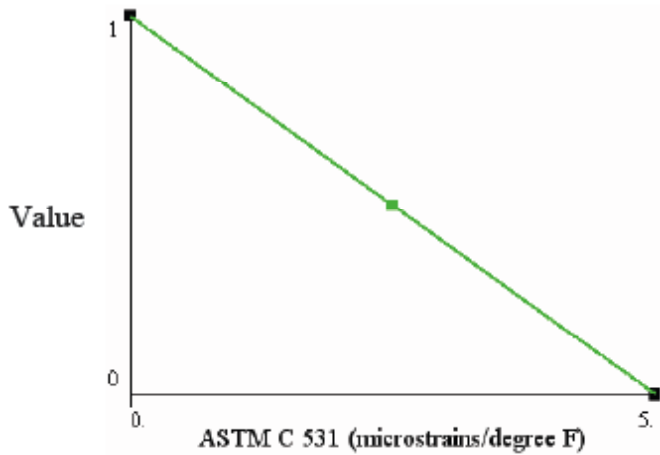


Figure 27. Thermal Coefficient SDVF (deviation from 5 microstrains/°F)

3.6.3 Shelf Life

The shelf life of a material is the length of time a manufacturer recommends a product can be stored unopened before the performance of a material is degraded. The unit for this measure is months. This function is continuous since the range of possible values is infinite. The function is increasing because materials with high shelf lives are preferred. The decision makers chose an upper bound of 60 months and a lower bound of 12 months. Figure 28 shows the SDVF for shelf life.

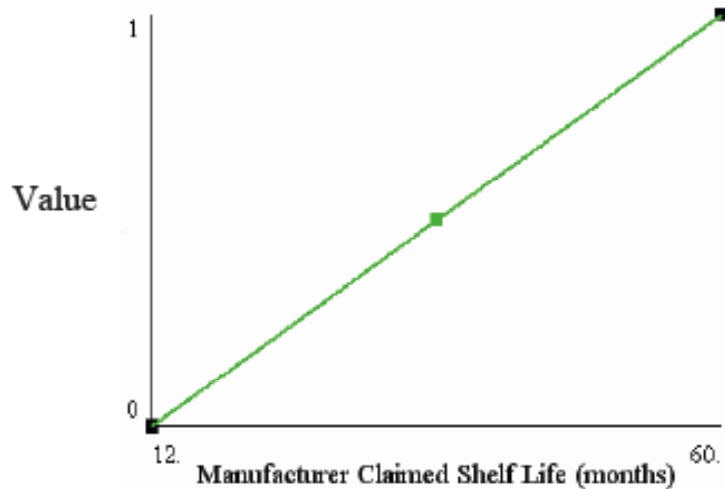


Figure 28. Shelf Life SDVF

IV. Results and Analysis

4.1 Overview

This chapter will present and analyze the rankings of spall repair products using steps seven, eight and nine of Shoviaks's 10-step VFT process. In step seven, alternatives will be scored on each measure in the hierarchy. In step eight, deterministic analysis will reveal the rankings of repair products as calculated by the Logical Decisions software program. In step nine, sensitivity analysis will be performed to determine what impact changes in weights will have in the ranking of alternatives.

Since hierarchy weighting is different for conventional and contingency repair scenarios, deterministic analysis will be performed separately for each. However, because most repairs will be conducted in a conventional, steady state repair scenario, sensitivity analysis will be discussed for this weighting only.

4.2 Alternative Scoring

The primary source of data for evaluation measures in this hierarchy was collected from product manufacturer's websites. It should be noted that many engineers caution against relying on data supplied by manufacturers. In many cases, independent lab tests do not back up manufacturer's claims on the results of material properties. For this reason, any data that was available from independent testing was used in place of manufacturer data. As more data becomes available through independent lab testing, this model should be updated to maximize the integrity of the model. Table 7 is a summary of data collected on each of the evaluation measures for the fourteen repair alternatives. All data except those in the shaded cells were collected from manufacturer specifications.

Table 7. Summary Matrix of Alternative Scores

Material Name	Set 45 HW	Set 45	FiveStar Highway Patch	Five Star Structural Concrete	Pavement SL	Pavement TR	Pavement VR	Pavement SLQ	Pavement 15	Pavement 5.0	Pavement EX	Pavement EX-H	ThoRoc 10-61C Rapid Cement	ThoRoc 10-60C rapid cement
Manufacturer	BASF Building Solutions	BASF Building Solutions	Five Star Products	Five Star Products	CeraTech	CeraTech	CeraTech	CeraTech	CeraTech	CeraTech	CeraTech	CeraTech	BASF Building Solutions	BASF Building Solutions
Cement Composition (in order of prominence)	Silica (crystalline quartz), fly ash, magnesium oxide	Silica (crystalline quartz), fly ash, magnesium oxide	Silicon Dioxide, Crystalline Silica, Silica Sand SiO ₂	Silicon Dioxide, Crystalline Silica, Silica Sand SiO	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Magnesium oxide, Phosphate (calcium/potassium/sodium), silica (crystalline quartz)	Magnesium oxide, Phosphate (calcium/potassium/sodium), silica (crystalline quartz)	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	Silica (crystalline quartz), fly ash, magnesium oxide, calcium carbonate	aluminum cement, portland cement, anhydrite, fly ash	alumina cement, portland cement, anhydrite, fly ash
Shrinkage	Low	Low	High	Low	Low	Low	Low	Low	Low	Low	Low	Low	High	High
\$/cf	\$50.00	\$50.00	\$50.00	\$70.00	\$116.30	\$116.30	\$116.30	\$116.30	\$116.30	\$116.30	\$122.00	\$116.30	\$13.49	\$13.49
Special Aggregates required?	Yes	Yes	No	No	Yes	No	No	Yes	No	N	Yes	Yes	N	N
Bond Strength (ASTM C 882 Slant Shear) @ 7 days	2190 psi	2250 psi	2000 psi	2500 psi	1665 psi	1930 psi	2400 psi	2866 psi	2000 psi	2780 psi	2450 psi	2500 psi	1480 psi	2160 psi
Early Strength (ASTM C 39 @ 3 hours)	3227 psi	5000 psi	3500 psi	2500 psi	3643 psi	3000 psi	4300 psi	3966 psi	3870 psi	3830 psi	2875 psi	3395 psi	3887 psi	3100 psi
Freeze/Thaw Resistance (ASTM C 666)	80%	80%	96%	>90%	>80%	>80%	>80%	>80%	>80%	>80%	>80%	>80%	100%	100%
Modulus of Elasticity (ASTM C 469)	4.90*10 ⁶ psi	4.18*10 ⁶ psi	3.5*10 ⁶ psi	3.8*10 ⁶ psi	2.21*10 ⁶ psi	2.77*10 ⁶ psi	2.27*10 ⁶ psi	1.70*10 ⁶ psi	3.3*10 ⁶ psi	3.4*10 ⁶ psi	2.72*10 ⁶ psi	4.56*10 ⁶ psi	4.6*10 ⁶ psi	4.4*10 ⁶ psi
Modulus differential from 4.5 * 10 ⁶ (10 ⁶ psi)	0.4	0.32	1	0.7	2.29	1.73	2.23	2.8	1.2	1.1	1.78	0.06	0.1	0.1
Compressive Strength (28 Day)	6317 psi	8500 psi	7280 psi	8000 psi	4257 psi	7114 psi	6580 psi	7483 psi	6300 psi	6100 psi	5870 psi	6535 psi	8293 psi	6893 psi
Coefficient of Thermal Expansion (ASTM C 531)	7.15 *10 ⁻⁶	7.15 *10 ⁻⁶	8.3* 10 ⁻⁶	5*10 ⁻⁶	2.55 *10 ⁻⁶	2.52X10 ⁻⁶	2.52X10 ⁻⁶	2.95X10 ⁻⁶	2.82 X 10 ⁻⁶	2.95*10 ⁻⁶	5.9* 10 ⁻⁶	6.13 X 10 ⁻⁶	6.8*10 ⁻⁶	7.0 *10 ⁻⁶
Thermal Coefficient Differential from 5 Microstrains (*10 ⁻⁶)	2.15	2.15	3.3	0	2.45	2.48	2.48	2.05	2.18	2.05	0.9	1.13	1.8	2
Shelf Life	12 months	12 months	12 months	24 months	36 months	36 months	36 months	36 months	36 months	36 months	12 months	12 months	12 months	12 months
Requires Bonding Agent?	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Hydrophobic?	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Lifts or Aggregate required?	Yes	Yes	No	Yes	Yes	No	No	Yes	No	No	Yes	Yes	No	No
Initial Set Time	76 min	13 min	25 min	30 min	11 min	12.5 min	17.5 min	4 min	12.5 min	4 min	70 min	37.5min	193 min	20 min
Initial Set time Differential from 45 min (minutes)	31	32	20	15	34	32.5	27.5	41	32.5	41	7.5	148	148	25

Key:

Data collected from WES Repair, Evaluation, Maintenance, and Rehabilitation (REMR) reports

Data obtained from the Wisconsin Department of Transportation

Data obtained from WES ERDC lab testing

Data obtained from engineers at AFCESA

4.3 Deterministic Analysis (Conventional Weighting)

In Chapter 3, SDVFs were created for each evaluation measure to convert the scores in Table 7 into unitless, normalized values from zero (least preferred) to one (most preferred). Next, the scores from Table 7 were inputted into Logical Decisions and the software calculated the corresponding unitless value for each measure determined from the SDVFs created earlier. Logical Decisions then used the additive value function to sum the products of these values and their predetermined weights (see Tables 4 and 5) for each evaluation measure to compute a total score for each alternative. The software then ranked each alternative based on its score, from high to low.

4.3.1 Deterministic Analysis on a Conventionally Weighted Scenario

Figure 33 shows the rank ordered list of alternatives using the decision maker’s weighting (Table 4) for a conventional repair scenario. Pavemend EX-H ranks the highest and earns the highest additive value function sum of 0.707.

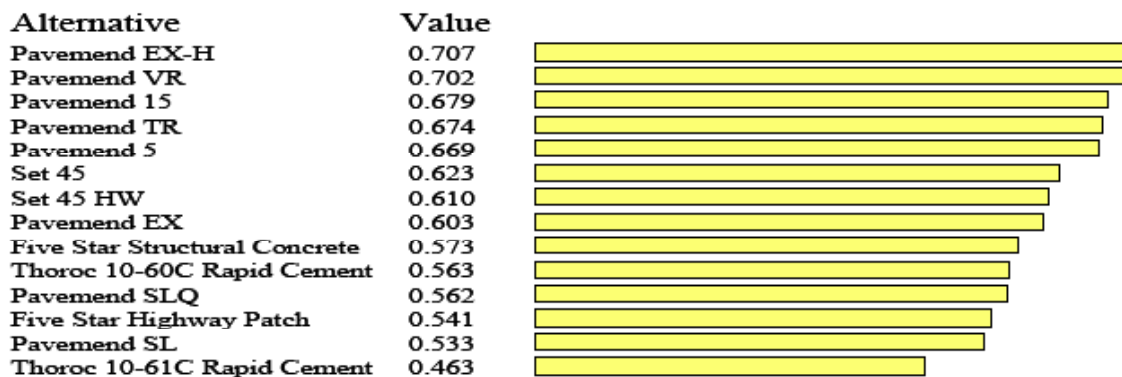


Figure 33. Alternative Rankings under Conventional Weighting

The top choice, Pavemend EX-H, outscored all other materials on the Desirable Material Properties value. It also scored highly on the Workability and Cost values. Although it has a score of zero on Shelf Life, it scores well enough on all other values to earn the top spot on the list. Pavemend VR scored well on all fundamental objectives, but was edged out by Pavemend EX-H on Desirable Material Properties and Workability. The worst alternative, Thoroc 10-61C Rapid Cement, ranked at the bottom due to poor scores on Desired Material Properties and Workability, and because it received a score of zero on Shelf Life.

Logical Decisions can also perform a stacked bar ranking by color-coding each individual measure. Figure 35 shows the stakeholders how each measure hurt or helped the value score of each alternative.

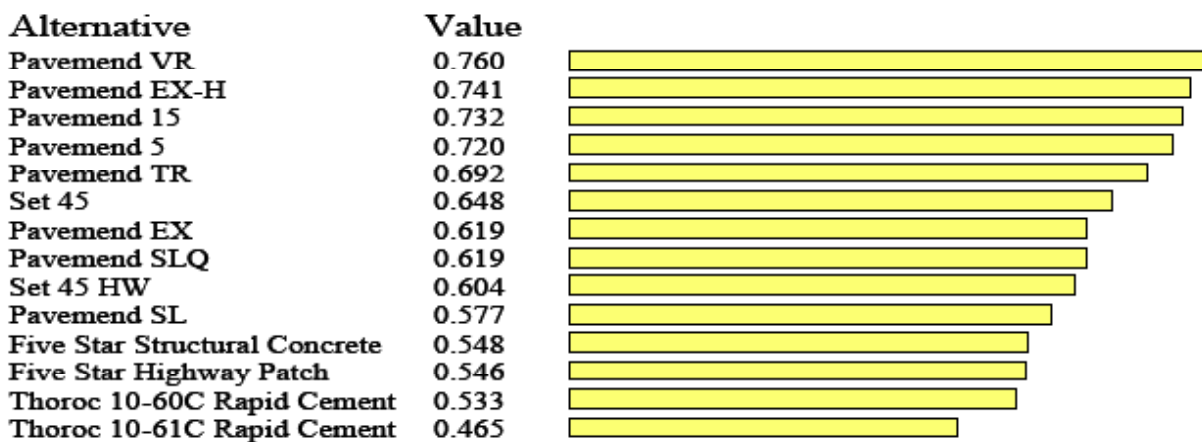


Figure 36. Ranking of Alternatives using Contingency Weighting

Figure 35. Alternative Rankings with Respect to Evaluation Measures (Conventional Weighting)

At the top of the list, Pavemend EX-H scores well on all measures within the Desirable Material Properties value. The next best alternative, Pavemend VR, is one of the few alternatives to score consistently well across all fourteen measures. In fact, only Pavemend VR, Pavemend 15,

60

Pavemend 5, and Pavemend TR received non-zero scores across all measures. Pavemend EX-H scores higher than the latter four due to its high score on Initial Set Time. The stacked bar ranking in Figure 35 does not show a score for early strength (ASTM C 39 @ 3 hours) for any alternatives since this value has a weight of zero under a conventional repair scenario weighting.

What are the characteristics that engineers look for in an ideal repair material?

Engineers look for a material with favorable physical properties needed to produce a long lasting repair. The material should have low drying shrinkage, high bond strength, and high compressive strength. It should be durable and able to withstand weather conditions such as freeze/thaw cycles. It should also be dimensionally compatible with the underlying substrate. This means that it should have a similar modulus of elasticity and coefficient of thermal expansion to the existing pavement. If a material meets the above criteria, it has a high chance of providing a long service life without early failure.

What characteristics and properties are uniquely important to military engineers in the repair of airfield pavements?

Military engineers look for a material that is low in cost, has favorable physical properties, with a long shelf life and that is easy to prepare and place. The material should be low in cost so that it does not strain financial resources, and unnecessarily waste taxpayer dollars, when a cheaper alternative may perform equally well. Military engineers need a material that will withstand heavy aircraft traffic; the material should have adequate physical properties to withstand these loads and avoid additional maintenance due to early failure. In order to avoid improperly placed repairs, a material is needed that is easy to prepare and place. The material should have high workability and require minimal repair site preparation.

What is the appropriate methodology for choosing the best pavement repair material?

Value-Focused Thinking was determined to be the best methodology to select pavement repair materials. VFT is an appropriate methodology to use when there are competing objectives in a decision. It is an objective tool that can balance all values a decision maker faces when selecting an ideal pavement repair material. The VFT process has the added benefit in that it sometimes leads the decision maker to think of possible alternatives that were previously unconsidered.

What are the available materials suitable for concrete spall repair?

The materials that were found to be suitable for concrete spall repair include products on the commercial market advertised for structural concrete repair applications. There are too many products on the market to list, however, so the decision makers chose materials for this model with good industry reputation, and properties that were favorable for good results.

Which material(s) should engineers select for concrete pavement spall repair?

This model found Pavemend VR, made by Ceratech Inc., to be the best candidate for partial depth spall repair. The material scored well on all measures in the hierarchy, and warrants field testing and possible use on operational airfields. In addition, four other Ceratech products scored high in this model and should also be considered:

Pavemend EX-H, Pavemend 15, Pavemend 5, and Pavemend TR.

5.3 Model Strengths

The value model provides a systematic, objective, and defensible method to rank repair product alternatives. The model is developed in a systematic series of steps that can be easily repeated or tailored to the needs of other stakeholders. By developing and weighting a value hierarchy before considering alternatives, the model is objective and free of bias that could unduly influence the selection of alternatives. By numerically scoring repair material alternatives with this model, the decision of which material to select can be defended with quantifiable confidence.

5.4 Model Limitations

This model requires extensive data and lab testing of repair materials in order for materials to be scored in the model. This testing is expensive and few manufacturers perform all the tests. For this reason, many alternatives with the potential to perform well in this decision had to be omitted for lack of data. In addition, many engineers find manufacturer-reported data to be suspect and often inflated. Due to the preponderance of manufacturer data used in this model, the results assume that manufacturers are properly performing and reporting results of material property tests. As materials undergo further lab testing, manufacturer data in this model should be replaced with data from independent lab testing to ensure the integrity of data in this model.

5.5 Future Research

As stated earlier, much effort is needed to perform independent testing of concrete repair materials. Although this may be expensive, it is well worth the cost to ensure that expensive materials are not fielded in operational use, and found to fail early and require successive repairs. Additionally, more research is needed to correlate material properties with field performance. Although generalizations can be made regarding properties that are favorable to produce long lasting repairs, minimum acceptable standards have not been established and agreed on by researchers.

5.6 Conclusions

This research shows that value-focused thinking is an appropriate methodology for selecting the best material to use for partial-depth rigid pavement spall repair. This research is unique since it is the first decision tool developed that will select the best repair material in this specific context. Many engineers still regard concrete repair material selection as “more of an art than a science.” This research provides the much needed science and objectivity to the material selection process.

The model indicates that Pavemend EX-H is the best alternative to use for conventional repair scenarios, and Pavemend VR is the best alternative for military engineers to use in contingency repair scenarios. This model shows that poor product candidates for pavement repair can be eliminated from consideration, avoiding the expense of testing and fielding inferior products. By implementing the decision strategy presented in this thesis, airfield pavement repairs will last longer and require less maintenance.

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