Rock Aggregate Management Planning for Energy Conservation: Optimization Methodology

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A mixed-integer programming approach is used to develop a rock aggregate management planning process. The basic objective is to minimize the use of aggregate materials and energy in transportation construction. Two models developed by the U.S. Forest Service are adopted for developing the planning process. Model 1, a minimum-path model, is used to evaluate the need of aggregate materials based on the least combined cost of vehicle operation, road maintenance, road construction and reconstruction, and environmental protection. Model 2, a rock aggregate shipment model, is utilized to allocate aggregate materials from the source to the project based on the least combined cost of transporting materials and material production. Since fuel cost accounts for more than 20 percent of the cost for hauling materials and material production, the process is considered to be energy-sensitive. The process is applied to the plan for developing and allocating aggregate materials in the Mount St. Helens volcano area of the Gifford Pinchot National Forest. The aggregate is used to reconstruct the system for transporting the timber from the forest's recurring annual harvest, as well as the salvage timber resulting from the Mount St. Helens volcanic eruption of May 18, 1980. The process is an extension of the urban transportation planning system process and can be applied to areas other than the forest land.

The construction of transportation facilities consumes billions of tons of rock aggregate annually. Like many other materials, the aggregate is in finite quantity and quality. It is nonrenewable and, depending on local geology, may be extremely limited. As a consequence, geographic distribution and quality often do not match requirements. The result is that hauling aggregate can consume large quantities of energy, and thus aggregate that is normally inexpensive can become quite costly.

The use of energy to transport aggregate materials has not been explicitly considered in aggregate management planning. However, energy consumption has become a significant factor in transportation planning because of transportation's heavy reliance on apparently inadequate oil supplies as a primary source of energy. Since expected oil supplies will probably not satisfy projected oil consumption in the future, conservation is considered as an appealing means for overcoming the fuel shortage.

The purpose of this paper is to develop a rock aggregate management planning process based on mixed-integer linear programming (MILP) techniques. The process would lead to minimizing the use of aggregate materials and energy in transportation construction. Its applicability has been demonstrated by a case study for the development of a rock aggregate management plan for the Mount St. Helens volcano area.

ENERGY SAVINGS AND AGGREGATE MANAGEMENT PLANNING

The objective of rock aggregate management planning is to establish a basic planning policy for evaluation, utilization, and conservation of rock aggregate resources in support of public needs. Aggregate resources are those occurrences of rock, gravel, sand, silt, and clay materials that are of sufficient quality to be utilized as construction materials. These resources exist in varying quantity and quality on U.S. lands and provide the major material source for road metal, concrete aggregate, asphalt pavement, and structural foundation reinforcement. They cannot be regenerated or replaced at a rate comparable with that of their extraction.

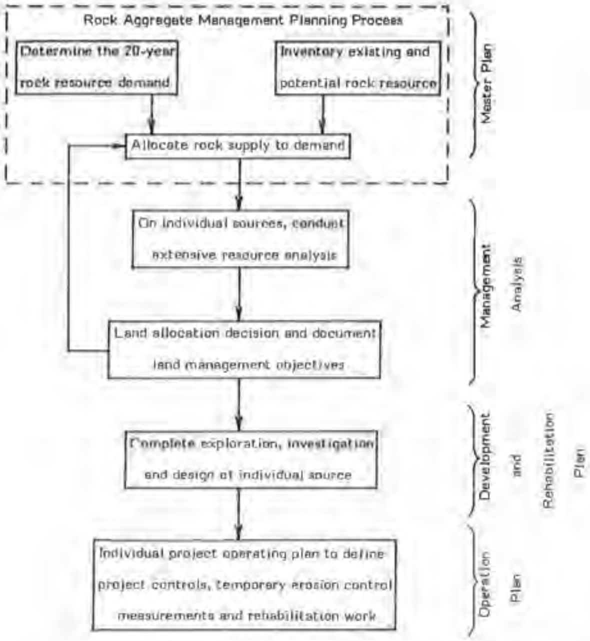
The rock aggregate management program as shown in Figure 1 indicates that the first step toward effective aggregate management is to make an inventory of all aggregate sources within the area of interest. It includes the determination of past activity for each site, estimation of quantity and quality remaining, assignment of a use potential for the future, and estimation of the work needed for continued resource development. Concurrently, a step is taken to identify the present and potential demand. Based on the quantity and quality of both supply and demand, the distribution pattern of the aggregate may be determined. The performance of these three steps in the first phase facilitates the necessary information for developing the master plan. The next phase of the program is to monitor the aggregate management plan and determine how well the plan meets the established land-management objectives and planned targets. This assessment provides information for improving the management plan. The last two phases are to develop a pit or quarry operating plan and specify requirements for surface restoration and temporary erosion measures needed to protect the aggregate resources. The major concern of this study is to develop a planning process for optimal use of aggregate and energy as shown in the first phase of the planning program. The costs of energy consumption of other phases are to be used as inputs to this process.

Since energy cost accounts for about one-third of rock aggregate transportation cost, the distance between the source and the project plays a key role in conserving energy. One way to reduce the haul distance is the optimization of road design for aggregates to make the best use of local materials. This can be achieved by providing alternatives for use of different levels of base, subbase, and asphalt pavement materials.

After the location, quantity, and quality of both supply and demand are identified, the plan for further energy conservation relies on the selection of the path with the least consumption of energy (or with the least haul cost) for transporting materials. The least-haul-cost algorithm then directs the material distribution pattern and will not allow aggregate cross haul. The selection of least-cost path depends on the vertical profile, horizontal alignment, and roadway characteristics, such as designed surfacing and system reliability, which all influence the fuel consumption of vehicles using a particular road. However, route characteristics are different from one path to another. Improving road conditions of a particular route may change another path selection in favor of that route. Thus the system improvement should be included in the path-selection process. Since the social and environmental impacts are of concern, the selection of a particular mode and a least-cost path should be subjected to both social and environmental constraints.

Beside transporting materials, material production also consumes fuel. As indicated by Kirby and Lowe (1), production activity can be divided into three components: site development, site restoration, and manufacturing process. Site development

Figure 1. Rock aggregate management planning program.



consists of providing an access road, clearing vegetation, removing overburden for opening a pit or a quarry, and transporting and setting up equipment that remains on site. Site restoration includes removing all equipment, cleaning and smoothing up the area, restoring a required thickness of topsoil, reestablishing vegetation, and obliterating the access road. The manufacturing process consists of pit or quarry development, material processing, and pit or quarry restoration. Fuel costs account for 15-20 percent of total costs involved in each of the above activities. Energy conservation in the manufacturing process can be achieved by the optimization of road design as indicated previously. The fuel consumption for site development and site restoration may be reduced if the demand is temporally and spatially continuous. Under this condition the number of pits or quarries needed to be open is minimal and the frequency of equipment movement may be reduced. Thus the time period of road construction becomes one of the important features in determining energy conservation. Note that action to reduce environmental impact also should be considered in each of the above activities.

The foregoing discussion indicates that almost all decisions concerning location, basic design, schedule, travel path, and materials used in constructing a roadway have profound implications for energy consumption. Decisions made today in which one alternative is chosen over another influence energy consumption now and, perhaps more important, have ramifications that will affect energy consumption for years to come. There is a pressing need to use an optimization technique developed in accordance with the aforementioned factors in making an effective aggregate management plan. This need has been recognized by the panel of a three-day workshop, Optimizing the Use of Materials and Energy in Transportation Construction, November 12-14, 1975, which was sponsored by the Federal Highway Administration, the Energy Research and Development Administration, the Federal Energy Administration and conducted by the Transportation Research Board (2).

PLANNING METHODOLOGY

Current Approaches

The formulation of an aggregate management planning process involves two major tasks. Given an existing network, the first task is to select a least-cost path based on a list of improvement options for various links, the projected traffic volume between various origin and destination pairs, and the selected optimal set of links to be improved or added to the existing network. In other words, based on the least combined cost of vehicle operation, system improvement, and road maintenance, the first task of the process chooses the optimal set of links to be improved or added and assigns the projected traffic to the new system simultaneously.

Various network design models have been developed to solve the least-cost-path problem (3,4). The present study selected a network model developed by Kirby, Wong, and Cox for single-commodity applications (5) and expanded by Ou, Cox, and Collett for multicommodity applications (6). Kirby's model is an MILP model that allows the project cost, vehicle operation cost, road maintenance cost, and the cost of environmental protection to be considered simultaneously to obtain an optimal solution. It has been used by many national forests across the country for timber sale appraisal. This model is referred to as Model 1 in the rest of this paper.

In Model 1, the network connectivity is modeled by a set of arcs. The nodes are numbered, and contiguous arcs are defined by common node numbers. Since the model represents the actual movement of vehicles through defined physical areas, both pits or quarries and roads for construction are also represented by nodes and arcs. In addition to connectivity, the arcs are defined by the following network parameters: length (miles or kilometers), capacity (vehicles), average speed (miles or kilometers per hour), nominal travel time (minutes), and average cost.

The second task in developing the aggregate management planning process is to derive an algorithm by which the process is able to allocate rock supply to demand based on the least cost of transporting materials and material production (including environmental protection). A rock aggregate shipment model developed by Kirby and Hager (7) was selected for this purpose. The model is still in the experimental stage and is referred to as Model 2. It is an integer linear programming model and employs a 0,1 type of variable that behaves as an integer variable.

The concepts and mathematical formulations of Models 1 and 2 as discussed above were adopted to develop a rock aggregate management planning process, presented in the next section.

Mathematical Programming Approach for Aggregate Management Planning

Based on the above discussion of factors related to a rock aggregate management plan, the mathematical derivation of an aggregate material allocation process follows. Let F be the set of destinations and G the set of origins for aggregate material type a. Let t be the index number of the time period and $\alpha_{am}X_{amijht}$ be the amount of type-a aggregate hauled from origin i to destination j via path h during period t [where α is the load per vehicle; X is the traffic volume; m (number of modes) = 1,2,3,...,M; i = 1,2,3,...,I; j = 1,2,3,...,J; and t = 1,2,3,...,T]. Finally, let $F_t \subseteq F$ be the set of destinations for which the material can be developed from the set of origins $G_t \subseteq G$ in the period of t.

Note that F_t and G_t will not necessarily contain all the elements of F and G, respectively. For example, if all types of needed aggregate materials are at destination j at time t, then $i \subseteq G$ and $j \subseteq F$ but $i \notin G_t$ and $j \notin F_t$.

The selection of origin i for developing $\alpha_{am}X_{amijht}$ and hauling it to destination j in time t is based on an objective function that minimizes the costs of total material, which includes transportation, site development, periodic fixed items, manufacturing process, site restoration, project construction, road maintenance, and environmental protection. An MILP formulation can be made by considering multiorigins, multidestinations, multimodes, and multiple time periods. The formulation may also take into account options of timing, location, quality and quantity of material development, as well as road construction and maintenance operations. It takes the following form:

$$\text{Minimize } Z = \sum_t WP_t \Bigg[\sum_i \Big(Y_i\phi_{it} + U_{it}\pi_{it} + W_i\psi_{it} + \sum_{amj} C_{ait}\alpha_{am}X_{amijt} + \sum_{amjh} C_{mijht}\alpha_{am}X_{amijht} \Big) + \sum_{bmijh} C_{mijht}\alpha_{bm}X_{bmijht} + \sum_r K_{rt}\theta_{rt} \Bigg] \tag{1}$$

Subject to supply constraints:

$$\sum_{mjh} \alpha_{am}X_{amijht} \leq V_{ait}\pi_{it} \tag{2}$$

Subject to:

$$\phi_{it} \leq \pi_{it} \quad \text{for all resource a, origin i, time period t} \tag{3}$$

Demand constraints:

$$\sum_{ihm} \alpha_{am}X_{amijht} = V_{ajt} \quad \text{for all resource a, destination j, time period t} \tag{4}$$

Link-capacity constraints:

$$\sum_{amijh \in \{L_{nt}\}} \beta_{it}(X_{amijht} + X_{bmijht}) \leq X_{nt} \quad \text{for all link n, capacity period t} \tag{5}$$

Project-construction-requirement constraints:

$$\sum_{amijh \in \{P_r\}} X_{amijht} + \sum_{bmijh \in \{P_r\}} X_{bmijht} \leq \sum_{\tau=1}^{t} g_r\theta_{r\tau} \quad \text{for project r, time period t} \tag{6}$$

Site-development constraints:

$$\sum_{\lambda=1}^{t} \phi_{i\lambda} \geq \pi_{it} \quad \text{for all origin i, time period t} \tag{7}$$

$$\sum_{\lambda=t}^{T} \Psi_{i\lambda} \geq \pi_{it} \quad \text{for all origin i, time period t} \tag{8}$$

$$\sum_{amjh} \alpha_{am}X_{amijht} \geq \phi_{it} \quad \text{for all origin i, time period t} \tag{9}$$

$$\sum_{amjh} \alpha_{am}X_{amijht} \geq \Psi_{it} \quad \text{for all origin i, time period t} \tag{10}$$

The variables are as defined below:

Notation	Variable
Z	Sum of material production cost and transportation cost
WP_t	Present value of 1 expended at beginning of time period t
Y_i	Fixed site-development cost at site i
U_{it}	Periodic fixed cost at supply site i for every operation period t
W_i	Fixed site-restoration cost (including environmental-protection cost) at site i
C_{ait}	Manufacturing-process cost per unit of aggregate material a at site i during time period t
X_{amijht}	Traffic volume between origin i and destination j hauling aggregate material a via route h by mode m during time period t
X_{bmijht}	Traffic volume between areas i and j for transporting commodity b via route h by mode m during time period t (where b = 1,2,3, ..., B and commodity b includes persons when mode m represents passenger vehicles)
C_{mijht}	Round-trip vehicle operating cost of mode m in time period t and route ijh including user's cost and operator's road-maintenance cost
K_{rt}	Sum of construction cost and environmental-impact cost of project r if the project is selected in time period t
π_{it}	1 if site i is operational in period t, 0 otherwise
ϕ_{it}, Ψ_{it}	Continuous nonnegative variables that behave like integers; that is, ϕ_{it} = 1 if the first operation period of site is period t, 0 otherwise, and Ψ_{it} = 1 if the last operation period of site i is period t, 0 otherwise
α_{am}, α_{bm}	Load per vehicle of mode m for aggregate material a and commodity b, respectively
θ_{rt}	1 if project r is built in period t, 0 otherwise
V_{ait}	Amount of aggregate material a available at site i during period t
V_{ajt}	Amount of aggregate material a required at destination j during period t
β_{it}	Portion of traffic flow from origin i in time period t that occurs during link capacity period
X_{nt}	Maximum permissible traffic over a period of time on link n in time t
$\{L_{nt}\}$	Set of routes ijh that use link n during time period t
$\{P_r\}$	Set of routes ijh that require the construction of project r
g_r	Arbitrary large constant greater than the overall traffic volume in all periods that use links covered by project r

In words, Equation 1 is an objective function that aims to minimize the sum of costs of resource-site development, periodic fixed items, fixed site restoration, manufacturing process, transportation, road construction, and related environmental protection. The transportation cost accounts for both vehicle-operating and road-maintenance costs. The road-construction cost considers any expense for improving the transportation system, including constructing new facilities and reconstructing existing facilities. The periodic fixed cost includes royalties, while the costs of other items are as defined previously.

Equations 2, 3, and 4 are constraints on the traffic generated in origins and attracted to destinations in time t. Equation 5 describes constraints on the capacity of a particular link in time t, while constraints related to project construction in terms of construction cost and environmental-protection cost are shown in Equation 6. Finally, Equations 7, 8, 9, and 10 present the site-development constraints that allow the site development to be a factor for determining the resource-site selection.

The purpose of considering multiple time periods is twofold. First, it provides an option for estimating project-construction cost with discount rate. In a regionwide transportation system improvement, the road construction or reconstruction usually takes place during more than one period of time. Second, the multiple time period allows the estimation of rock aggregate needs in different periods of time that could be used to determine the economic feasibility of opening a new pit (or quarry) or reopening an old pit (or quarry). The site-development costs are substantially different between a new pit (or quarry) and an old one.

It should be noted that in the development of Model 1 for minimum-path network analysis, both lower bounds and higher bounds of the resource quantity in terms of supply and demand were considered. Such a consideration is a requirement to achieve an optimization solution. The first minimum user's cost path through the transportation system is generated by Martin's standard labeling algorithm (8), while the next minimum paths are found by a modified Hoffman-Pavely algorithm (9).

The derived optimum path must be included in the set of paths derived from the n best user-path algorithms. The best or second-best user path may not be the optimum path subject to other costs and constraints. The relationship of the best user path to the optimum path is a function of user numbers or traffic volume and its ability to offset other costs and constraints. In a low-volume or short-planning-horizon situation it may be difficult to obtain this route by utilizing a minimum-user-cost algorithm. Kirby and others have suggested a simultaneous solution to this type of problem by utilizing conservation-of-flow equations within the MILP application (3). In a multimode, multitrip-purpose, multitime-period situation, this usually creates a very large and unyielding problem. The advantage of using a minimum-user-cost-path algorithm is that it causes many superfluous or spurious combinations to be pared off.

Aggregate Management Planning Process

In accordance with the above theoretical framework, a rock aggregate management planning process was developed. It consists of the following steps:

1. Inventory (land use, rock aggregate and other resources, population, traffic, and transportation facilities);
2. Land-use forecast;
3. Trip generation;
4. Modal split;
5. Trip distribution, network assignment, and project selection;
6. Estimation of rock aggregate demand;
7. Examination of the impact of rock haul on general traffic and repetition of steps 3-6 if the impact is significant;
8. Estimation of fixed cost, manufacturing cost, transportation cost, and placement cost;
9. Allocation of rock aggregate supply to demand; and
10. Evaluation of the difference between the resultant rock-haul traffic and that estimated in step 7 and repetition of steps 3-9 if the difference is significant.

The sequence of these steps is shown in Figure 2.

The first step includes an inventory of existing traffic throughout the whole region of interest together with inventories of land use, rock aggregate and other resources, socioeconomic characteristics of the population, and the existing transportation facilities. The second step is to forecast the land use that should occur in the forecast period. The next two steps are to predict the traffic demand by mode that may be anticipated and the way in which this will occur throughout the region. The fifth step is composed of an optimization procedure of trip distribution, network assignment, and project selection. It is carried out by Model 1, the minimum-path model that uses the least combined cost in terms of vehicle operation, road maintenance, road construction, and environmental protection. Step 6 is to estimate the rock aggregate demand by types of material such as plant-mix, base, subbase, and subgrade alteration and by periods of project construction. The option of subgrade alteration is to use native material for the substitution of base and/or subbase. It is designed to conserve high-quality rock and reduce fuel consumption. The seventh step is to examine the impact of traffic generated by hauling rock aggregate on the general traffic flow. If the impact is significant, it may change the system improvement and therefore the need for rock aggregate. This would require a repeat of the process from steps 3 to 6. The eighth step includes estimating various costs related to rock aggregate allocation, such as fixed items, manufacturing, rock hauling, and placement. As indicated previously, the fixed costs are the sum of costs for developing, maintaining, and restoring a quarry or pit as well as for setting up and removing equipment. Manufacturing, rock hauling, and placement are costs per unit volume of a specific type of material. As shown in Figure 2, the haul cost is estimated by using Model 1 in accordance with the proposed network and the future traffic (including rock haul).

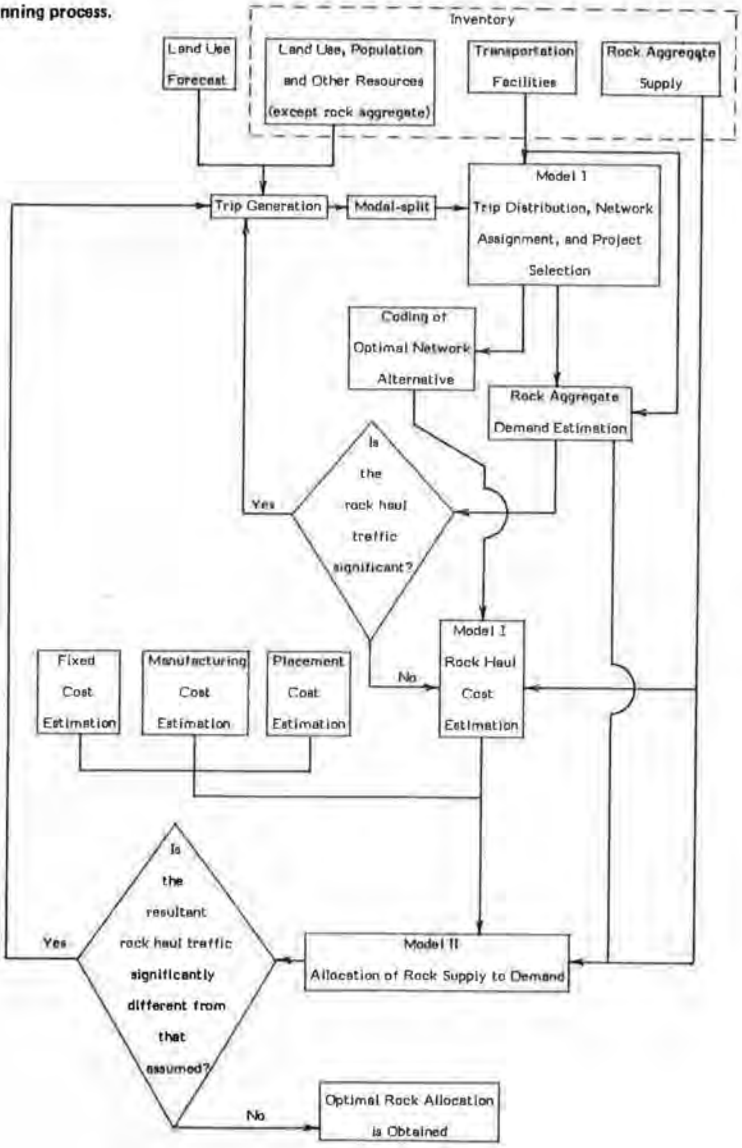
The ninth step is to allocate the rock supply to demand by using Model 2, the rock aggregate shipment model. The inputs of the model are the cost items as mentioned together with the quantity and quality of rock aggregate supply and demand. The outputs of Model 2 include both cost and material summaries. The cost summaries contain material manufacture, material transportation, and the sum of the two. They are specified by type and period for each road. The material summaries include (a) material manufactured at each quarry or pit by type and period, (b) flow of material from quarry or pit to road by type and period, (c) amount of material placed on each road by type and period, and (d) amount of subgrade alteration on each road and period during which the treatment is done.

The last step is to examine the actual impact of traffic generated from hauling rock aggregate on the general traffic flow. If the actual impact is significantly different from that estimated in step 7 and used in step 8, the iteration of the process from steps 3 to 9 must continue. However, if data for both rock aggregate supply and demand are available, the execution of steps 8 and 9 may result in a primary rock aggregate allocation.

Note that steps 1 to 5 are consistent with the Urban Transportation Planning System (UTPS) process. Thus the rock aggregate management planning process can be considered as an extension of the UTPS process.

The case study below demonstrates the application of the rock aggregate management planning process to the Mount St. Helens volcano area of the Gifford Pinchot National Forest, Skamania County, Washington.

Figure 2. Rock aggregate management planning process.



CASE STUDY

Figure 3 shows the forest transportation system in the Mount St. Helens volcano timber salvage area. A great portion of this system was damaged by the volcanic eruption of May 18, 1980. In order to provide access for transporting salvage timber and other land-management activities, the system must be improved. The plan for system reconstruction was carried out by using the rock aggregate management planning process.

Three items for the inventory were timber harvest, transportation system, and rock aggregate resources. It was estimated that 1250 million board feet (mmbf) of timber with 700 mmbf of salvage sale, 300 mmbf of green sale, and 250 mmbf of private sale are to be hauled through the volcano-area transportation system in the next two seasons. The examination of road conditions found that the system requires 44.1 miles (71 km) of asphalt pavement overlay and 103.1 miles (165.9 km) for rock aggregate surfacing. In addition, 62.5 miles (100.6 km) of forest road may require new asphalt pavement. The need for pavement was justified by the economic feasibility of construction costs versus savings of vehicle-operating and road-maintenance costs. The primary investigation of rock aggregate supply indicated that there are 18 candidate quarries with a total of 1 263 000 yd^3 (965 627 m^3) including 240 000 yd^3 (183 492 m^3) of plant-mix, 482 000 yd^3 (368 513 m^3) of base, and 541 000 yd^3 (413 622 m^3) of subbase.

Since the main purpose of improving the system in the volcano area is to haul salvage timber, the second step of the planning process, the land-use forecast, becomes unnecessary. By using Model 1, steps 3 to 5 of the process were performed to determine the road segments of the 62.5 miles for pavement. The result of an optimal solution indicated that 25 miles (40.2 km) of the 62.5 miles would be more economically efficient if they were paved. However, 4.5 miles (7.2 km) of the road recommended for pavement was considered infeasible from the point of view of road management. It should be noted that prior to the analysis of steps 3 to 5, two policy options can be made to improve the 62.5-mile system. The first option is the "do-nothing" alternative, i.e., leave the system as it is and without improvement. Based on this scenario, it would cost $15 million (including both vehicle-operating and road-maintenance costs) for hauling 700 mmbf of salvage timber. The second option is to

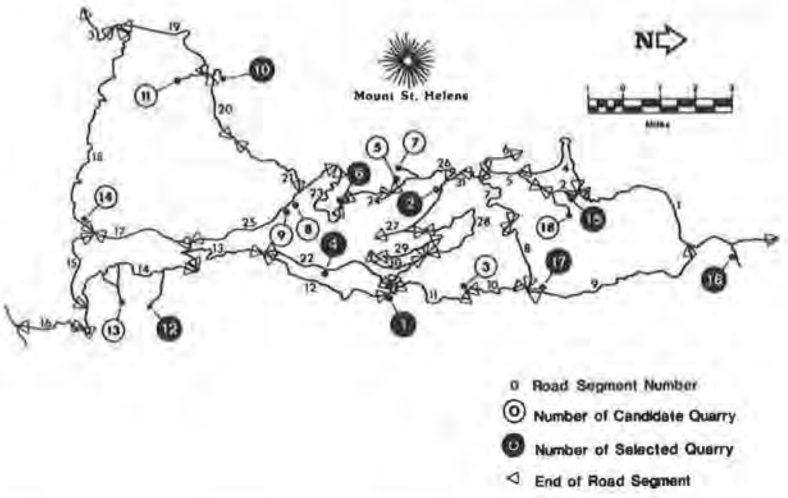


Figure 3. Location of quarries and road segments in Mount St. Helens volcano timber salvage area.

Table 1. Aggregate demand by roads and aggregate supply by quarries.

Project Demand by Road Segment	Source Supply by Quarry	Rock Aggregate (yd^3)			
		Total	Plant-Mix	Base	Subbase
R01	Q16	22 950	22 950	0	0
R02	Q15	6 200	0	1 450	4 750
R03		0	0	0	0
R04	Q15	28 200	0	9 800	18 400
R05	Q15	10 750	0	6 250	4 500
R06	Q02	6 050	0	3 750	2 300
R07		16 800	11 600	0	5 200
	Q07	11 600	11 600	0	0
	Q07	5 200	0		5 200
R08	Q17	4 250	4 250	0	0
R09	Q17	26 100	26 100	0	0
R10	Q17	5 700	5 700	0	0
R11	Q04	3 200	3 200	0	0
R12	Q04	14 600	0	14 600	0
R13	Q04	25 600	9 530	16 070	0
R14	Q12	5 700	0	5 700	0
R15		0	0	0	0
R16	Q12	18 800	8 800	10 000	0
R17	Q04	9 300	9 300	0	0
R18		0	0	0	0
R19	Q10	6 450	0	6 450	0
R20	Q10	4 150	0	4 150	0
R21	Q10	4 150	0	4 150	0
R22	Q04	6 300	6 300	0	0
R23	Q06	9 850	0	5 750	4 100
R24	Q06	14 750	0	3 000	11 750
R25		0	0	0	0
R26	Q06	2 900	0	2 900	0
R27	Q02	16 800	0	5 100	11 700
R28		19 200	0	9 000	10 200
	Q01	10 200	0	0	10 200
	Q04	9 000	0	9 000	0
R29		11 930	0	7 730	4 200
	Q01	4 200	0	0	4 200
	Q04	7 730	0	7 730	0
R30		8 040	0	6 050	1 990
	Q01	1 990	0	0	1 990
	Q04	6 050	0	6 050	0
R31	Q02	8 300	0	3 800	4 500
Total		317 020	107 730	125 700	83 590

Note: 1 yd^3 = 0.764 55 m^3.

pave all of the 62.5 miles of forest roads. This option would require $6 250 000 of pavement cost and $9 659 000 of haul cost, or a total of about $16 million of transportation cost to haul the timber volume mentioned. However, with consideration of 20.5 miles (33 km) for pavement, it only costs $14 049 000 for timber haul and road reconstruction. The savings of the selected alternative compared with the "do-nothing" and "pave-all" alternatives are $943 000 and $1 860 000, respectively. Since fuel cost accounts for more than 20 percent of haul cost and road-construction cost, the selected alternative would conserve from $188 600 to $372 000 worth of fuel.

In step 6, estimates were made for the rock aggregate demand of system improvement including 44.1 miles (71 km) for asphalt overlay, 103.1 miles (165.9 km) for rock aggregate surfacing, and 20.5 miles (33 km) for new asphalt pavement. The projected demand would be 395 000 yd^3 (302 000 m^3) of aggregate with 107 730 yd^3 (82 365 m^3) of plant-mix, 125 700 yd^3 (96 104 m^3) of base, and 83 590 yd^3 (63 909 m^3) of subbase. The result of the analysis in step 7 indicated that the traffic demand of hauling aggregate is relatively small when compared with the traffic generated by transporting timber. Thus the effect of rock haul on aggregate demand was considered to be insignificant. Based on the estimated supply and demand, haul costs per unit of aggregate from each candidate quarry to road segments were estimated by using Model 1.

After completion of step 8, the estimated costs, including fixed items, manufacturing, transportation, and placement along with the quantities of demand and supply, were used as the inputs to Model 2 for rock aggregate allocation. The results of step 9 are presented in Table 1.

As shown in Table 1, nine quarries were selected from the 18 candidate quarries. This material allocation pattern would result in $592 000 of haul cost, $1 209 000 of placement cost, $2 000 000 manufacturing process cost, $94 000 of site-development cost, and $4500 of site-restoration cost, for a total of $3 899 500. This total is approximately 20 percent of the $20 million project for constructing and reconstructing the transportation system in the Mount St. Helens volcano timber salvage area. In this study the fourth type of material, the subgrade alteration, which would use native material as a substitute base and/or subbase, was not considered. The system improvement was scheduled for one point of time; therefore only one time period was used in this particular application. The traffic of rock haul was found to be insignificant when compared with the general traffic. Thus step 10 of the process was not executed. The result of this study provided a general guideline for improving the volcano-area transportation system, which is planned to be reconstructed in spring 1982.

CONCLUSION

As part of the planning process to develop a forest rock aggregate management plan, the Gifford Pinchot National Forest, of the U.S. Department of Agriculture, Forest Service, used the available techniques from the Forest Service and developed a rock aggregate management planning process that can be applied to areas other than the forest land. The process could generate an optimal rock aggregate allocation pattern based on the least cost as well as least fuel consumption.

The planning process has been applied to the Mount St. Helens volcano timber salvage area to determine the rock aggregate needs and to allocate them for transportation system construction. The result of the application indicated that the process allows the examination of complex options and alternatives conveniently. The planner may use it to develop an aggregate management plan for a specific project or for a region under a pressing deadline. Its consideration of fuel consumption may increase the planner's confidence in optimal use of aggregate materials and energy.

ACKNOWLEDGMENT

We wish to express our appreciation to Peter Wong, Malcolm W. Kirby, and Allan J. Hessell for their helpful comments. The provision of necessary data for this project by William Powell and Allen Morrissette is acknowledged. Special thanks go to Melroy H. Teigen and David B. Trask for their support. We of course accept sole responsibility for the contents of this paper.

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Publication of this paper sponsored by Committee on Mineral Aggregates.

Soil Support Value–A New Horizon

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The soil support value of the American Association of State Highway Officials interim guide for the design of flexible pavement is given a new horizon. It is shown that the soil support scale can be expressed in terms of a normalized model. This model relates the dynamic load capacity of a subgrade soil to its static strength. The model was verified by using five different materials that ranged from gravel, sand, and clay to clayey silt.

The determination of a flexible pavement structural thickness (surface, base, and subbase) depends on two major factors--traffic and subgrade strength. Existing design procedures call for different subgrade strength parameters or strength-scaling factors [elastic modulus, resilient modulus, California bearing ratio (CBR), soil support value (SSV), etc.]. The American Association of State Highway Officials (AASHO) design method, in particular, uses a subgrade strength-scaling factor called an SSV. This factor was assigned an empirical scale with values from 3 to 10. Point 3.0 on the soil support scale represents the roadbed soils at the AASHO Road Test. As pointed out by the AASHO interim guide, the units of the SSV have no direct relationship to any procedure for testing soils. Therefore, it is necessary for each design agency to establish a correlation between SSV and some testing procedure before this guide can be used for flexible pavement design.

In this paper, it is shown that the empirical soil support scale is related to a significant physical property of the subgrade material in question. This relationship is independent of sample and test variables and it is unique in its nature for the particular subgrade material under consideration.

BACKGROUND

The basic design equation, developed from the results of the AASHO Road Test, is valid for one SSV, which represented the roadbed soils and the conditions that existed at the test site and during the time of test. Consequently, it was necessary to assume an SSV scale to accommodate the variety of soils that could be encountered at other sites (1,2). This led different highway engineers to assume different SSVs for the same subgrade materi-