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轻质土动力特性研究进展

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摘　要　轻质土具有轻质、高强、保温、隔振、环保、经济等优点, 在路基回填、软基处理、隧道减荷等岩土工程领域具有广阔的应用前景. 作为新型土工材料, 交通荷载、地震荷载、波浪荷载等振动荷载对轻质土力学特性的影响引发众多关注. 本文阐述了配合比(轻质材料含量、固化剂掺量、含水率等)、应力状态、振动频率、干湿交替和冻融循环等因素对轻质土动力特性的影响规律, 总结了轻质土动剪切模量和阻尼比计算模型. 研究发现水泥等固化剂的使用大幅提升了轻质土抵抗动荷载的能力, 轻质土独特的孔隙结构可显著提高其隔振效果, 干湿、冻融循环会导致轻质土动力学性能劣化, 在实际工程中可通过设置防水层延长其服役寿命. 通过模型试验和数值模拟验证了轻质土在实际工程中具有良好的动力稳定性和耐久性. 目前轻质土动力特性研究尚处于起步阶段, 新型固废轻质土动力学性能尚未深入研究, 复杂环境因素与动荷载耦合作用下轻质土的作用机理、力学性能和本构模型研究, 以及轻质土在不同工程背景下的设计施工方法研究仍需探索.

关键词　轻质土; 动模量; 阻尼比; 动强度; 工程应用
分类号　TU435

Research progress on the dynamic characteristics of lightweight soil

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ABSTRACT　Lightweight soil is a novel technological material that boasts characteristics such as low density, high strength, thermal insulation, vibration isolation, environmental friendliness, and cost-effectiveness. These features make it highly suitable for a wide range of applications in geotechnical engineering, including roadbed backfill, soft foundation treatment, and tunnel load reduction. The influence of vibration loads resulting from transportation, earthquakes, waves, and other factors on the mechanical properties of lightweight soil has garnered considerable attention in recent research. This paper expounds on the influence of factors on the dynamic deformation characteristics and dynamic strength properties of lightweight soil. These factors include the mix ratio (such as the content of lightweight materials, dosage of curing agent, and moisture content), stress state, vibration frequency, dry–wet alternation effect, and freeze–thaw cycle. Additionally, we summarise the calculation model for the dynamic shear modulus and damping ratio of lightweight soil. The findings reveal that the incorporation of curing agents, such as cement and fly ash, substantially improves the resistance of lightweight soil to dynamic loads. Additionally, the distinctive pore structure of lightweight soil markedly enhances its vibration isolation effect. As dynamic strain increases, there is a nonlinear decrease in the dynamic modulus of lightweight soil while the damping ratio increases nonlinearly. Adjusting the content of lightweight materials and the dosage of curing agents can markedly improve the seismic reduction effect of lightweight soil, thus granting it greater dynamic stability. The coupling effects of dry–wet cycles,

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freeze–thaw cycles, and dynamic loads may lead to a degradation in the dynamic performance of lightweight soil. To extend its service life in practical engineering applications, the implementation of a waterproof layer is recommended. Model tests and numerical simulations substantiated the commendable dynamic stability and durability of lightweight soil in real-world engineering scenarios. Finally, following a comprehensive literature review, this paper identifies potential research directions. The study of dynamic characteristics in lightweight soil is still in its infancy, with the dynamic properties of novel solid waste lightweight soil remaining largely unexplored. Further exploration is required to fully understand the response mechanisms, mechanical properties, and constitutive models of lightweight soil under the combined effects of complex environmental factors and dynamic loads. Additionally, there is a need for continued research into the design and construction methods of lightweight soil across various engineering settings. In conclusion, this paper serves as a valuable reference for investigating the dynamics of lightweight soil and its extensive application in geotechnical engineering.

KEY WORDS lightweight soil; dynamic modulus; damping ratio; dynamic strength; engineering application

自十九大报告提出交通强国战略以来，我国基础设施建设日新月异，建设均衡、高质量的交通运输网络是中国现代化建设的基础. 然而我国幅员辽阔、地形复杂，分布广泛的特殊地基、软弱地基成为制约我国基础设施建设的重要因素. 为解决地基强度、稳定性、沉降变形等问题，各种地基处理方法快速发展，新的土工材料层出不穷，轻质土由于具有质量轻、强度高、比强度高、柔韧性强、传热系数低、使用周期长、环保、经济等优点脱颖而出.

轻质土是指将原料土（砂土、粉土、黏土、淤泥等）、轻质材料（聚苯乙烯、聚氨酯、气泡、橡胶颗粒等）、胶凝材料和水充分混合固化后形成的，密度小于天然土体的轻质土工材料. 根据轻质材料的不同可将轻质土分为聚苯乙烯（EPS）轻质土、泡沫轻质土和橡胶轻质土. 近年来为实现节能减排和固废资源化利用，使用粉煤灰、矿渣、赤泥等具备潜在活性的工业固废作为胶凝材料制备的新型轻质土，如碱渣轻质土、电石渣轻质土、废石膏轻质土等引发广泛关注[1–2]. 研究发现轻质土可用于解决路基不均匀沉降、桥头跳车等问题，还可起隔热、减震的作用，用于地下建（构）筑物保护[3–5]. 2015 年，我国颁布的《公路路基设计规范》（JTGD30—2015）[6] 中增添了轻质材料路堤的设计方法，以此规范为基础促进了轻质土的广泛应用. 在轻质土的工程应用中，不可避免的会遇到地震荷载、列车运营荷载、交通荷载、波浪荷载等振动荷载，振动荷载可能引起土体失稳、破坏、振陷等，对工程安全产生较大影响. 此外，试样在循环荷载作用下会产生渐进损伤，其破坏强度与静载强度有显著差异[7]，因此参考静载条件下轻质土强度进行工程设计存在较大安全隐患. 深入研究各因素（配合比、应力状态、振动频率、干湿循环、冻融循环等）作用下轻质土动力学特性变化规律，对轻质土的工程应用具有重要意义.

本文对轻质土动力特性相关研究进行综述，主要包括循环荷载下轻质土动模量、阻尼比变化规律，轻质土动强度、动强度指标、临界动应力和累积变形规律，并详细介绍了轻质土动力特性模型试验和数值模拟的研究进展；最后对现有研究的局限性进行展望.

1 轻质土动力变形特性试验

1.1 轻质土初始动剪切模量、阻尼比

共振柱[8–11] 和弯曲元试验[12] 是进行小应变范围（动应变幅值小于 10^{-4}）内轻质土动力特性研究的主要方法，此外，有学者通过动三轴试验[9, 13]、循环单剪试验[14–15] 等间接测量轻质土初始动剪切模量（$G_{\max}$）. 相同条件下，共振柱和弯曲元试验测得的轻质土 $G_{\max}$ 大于动三轴试验结果[8–9].

国内外学者对小应变下轻质土动剪切模量（G_d）和阻尼比（λ）变化规律开展众多研究，发现轻质材料的添加使轻质土具有低动剪切模量和高阻尼比[14, 16]；图 1 反映了气泡含量和动剪应变对泡沫轻质土 G_d 和 λ 的影响规律，随动剪应变幅值的增加，小应变范围内轻质土 G_d 非线性减小，而 λ 非线性增大，气泡质量分数（w_f）的增加使泡沫轻质土 G_d 显著减小，λ 明显增大[16]. 轻质材料含量的增加使试样内部孔隙增多，应力波传递过程能量损失增大，故轻质土最小阻尼比（$\lambda_{\min}$）逐渐增大；水泥掺量的增加使颗粒间胶结作用增强，振动过程中能量损耗减小，故 $\lambda_{\min}$ 逐渐减小；相较而言，固结围压对轻质土 $\lambda_{\min}$ 的影响较小，$\lambda_{\min}$ 随固结围压增大而减小. Pistolas 等[17] 认为橡胶粒径对轻质土 $\lambda_{\min}$ 有一定影响，随橡胶粒径比的减小，$\lambda_{\min}$ 逐渐增大；李晓雪等[18] 则认为粒径对橡胶轻质土 $G_{\max}$ 和 $\lambda_{\min}$

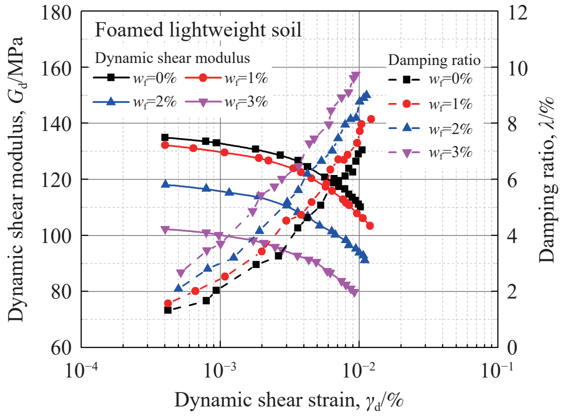

图 1　泡沫轻质土共振柱试验结果[16]

Fig.1　Results from the column tests on foamed lightweight soil[16]

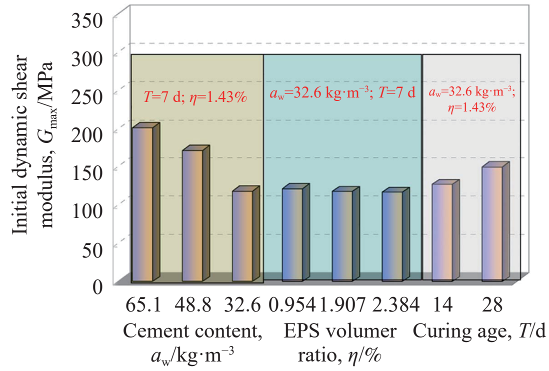

图 3　轻质土配合比和养护龄期对 G_{max} 的影响[21]

Fig.3　Effects of mix proportion and curing age on the G_{max} of lightweight soil[21]

的影响可以忽略.

如图 2 和图 3 所示轻质材料体积分数(η)、单位体积轻质土中固化剂质量(a_w)、养护龄期(T)和固结围压(σ_3)对轻质土 G_{max} 影响显著[8, 12, 19–21]. 轻质土 G_{max} 随水泥(粉煤灰)掺量和固结围压的增加而增大[15, 17]; 随橡胶或 EPS 含量的增加, 轻质土 G_{max} 逐渐减小, 研究发现 EPS 颗粒的添加可使其 G_{max} 减小约 30% ~ 34%[13, 21], 当固化剂掺量较高时, 轻质土 G_{max} 主要取决于固化物强度, EPS 颗粒的影响明显减弱[22]; 此外, 橡胶颗粒的粒径及级配亦对轻质土 G_{max} 存在较大影响[11–12]; 气泡含量的增加使得泡沫轻质土内部孔隙显著增大, G_{max} 亦逐渐减小[15, 17]; 养护龄期越长水泥固化作用越明显, 轻质土 G_{max} 也随之增长, 当养护龄期超过 28 d 后, 轻质土 G_{max} 增长速率明显减小[14].

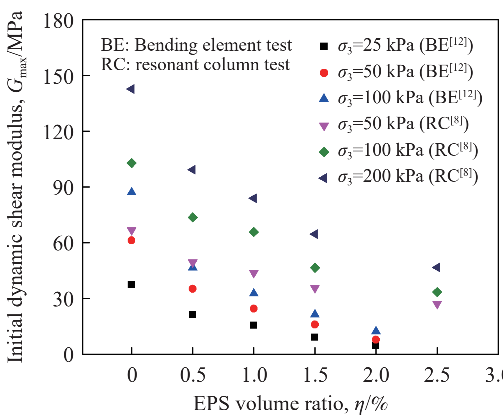

图 2　EPS 掺量对 EPS 轻质土 G_{max} 的影响[8, 12]

Fig.2　Effect of EPS content on the G_{max} of EPS lightweight soil[8, 12]

钟晓凯[22] 对比分析了三角波、正弦波和矩形波对污泥固化轻质土 G_{max} 的影响, 研究发现, 三角波作用下污泥固化轻质土的 G_{max} 最大, 正弦波次之, 矩形波最小; 一定范围内振动频率的增加可增强轻质土 G_{max}[23–24]. 初始应力状态会对轻质土 G_{max} 产生较大影响, EPS 轻质土 G_{max} 随初始平均有效固结压力的增加近似线性增长, 随初始固结应力比和主应力轴旋转角的增加逐渐减小, 初始中主应力系数的影响较小[25–26]. 杨爱武等[27] 发现冻融循环导致泡沫轻质土结构性破坏, G_{max} 降低, 且冻结温度越低、冻融循环次数越多, G_{max} 损失量越大. 表 1 汇总了国内外学者建立的各类轻质土 G_{max} 计算模型, 由表可知, 目前轻质土 G_{max} 计算模型多针对橡胶颗粒轻质土和 EPS 轻质土, 而泡沫轻质土的 G_{max} 计算模型尚未有学者进行深入研究.

目前关于轻质土初始动剪切模量和阻尼比的研究多关注其宏观变化规律, 尚未有学者从微观层面解释轻质土初始动力变形特性的变化机理, 不同种类轻质土初始动力变形特性的异同亦少有学者进行系统研究.

1.2　轻质土动模量、阻尼比

众多学者通过动三轴、空心圆柱扭剪、循环环剪、循环单剪等试验研究中等变形和大变形阶段轻质土动力变形特性, 分析轻质土动弹性模量和阻尼比变化规律. 轻质土中固化剂的添加可显著增强其动弹性模量, 而轻质材料含量的增加则在一定程度上增强了轻质土阻尼比, 两者耦合作用使轻质土具有良好的动力变形特性, 研究发现 EPS 轻质土的动态承载力约为重塑土的 1.5 ~ 3 倍, Hardin–Drnevich 模型可用于描述轻质土动力变形特性[32]. 如图 4 所示, 轻质土动剪切模量随动应变增加不断衰减, 水泥掺量和围压的增大可提高轻质土动剪切模量, 橡胶含量的增加则使得动剪切模量显著下降; 橡胶轻质土和泡沫轻质土的阻尼比均随动剪切应变增加而增大, EPS 轻质土的阻尼比则呈现先增大后减小最终增大的变化趋势[9, 16, 24].

表 1　轻质土初始动剪切模量计算公式

Table 1　Calculation model of the initial dynamic shear modulus of lightweight soil

Material type	Calculation model	Model parameters	Test type	Ref.
Sand−EPS mixtures	$G_{\max}=A_0F\left(e_{\mathrm{eq}}\right)\left(\sigma_3'\right)^{nF_n(e_{eq})}$	A_0, n are the fitting parameters. σ_3' is effective confining pressure. $F(e_{\mathrm{eq}})$ is a power function related to the void ratio of soil.	Resonant column	[8]
Rubber−sand mixtures	$G_{\max}=111\left(\dfrac{\sigma_c'}{p_0}\right)\times0.1^X$	σ_c' is effective confining pressure. p_0 is atmospheric pressure. X is the rubber content.	Resonant column	[9]
Clay−EPS beads lightweight soil	$G_{\max}=\left(p_1+p_2a_{\mathrm{w}}T^{p_3}+p_4V_{\mathrm{e}}^{p_5}\right)\left(\dfrac{\sigma_{\mathrm{c}}}{\sigma_{\mathrm{r}}}\right)^n$	p_1, p_2, p_3, p_4, p_5 and n are the fitting parameters. a_{w} denotes the mass of cement per volume of the lightweight soil. T is the curing age. V_{e} is the mixed ratio of EPS. σ_{c} is confining pressure. σ_{r} =1 kPa, is the reference stress.	Dynamic triaxial	[13]
Rubber−sand mixed soil	$G_{\max}=aX^{-1.97}+6.5$ $a=8.2721p^{0.5594}$	X is the rubber content. p is confining pressure.	Resonant column	[18]
EPS−sand mixtures; Rubber−sand mixtures	$G_{\max}=A\left(\dfrac{p'}{\sigma_{\mathrm{r}}}\right)^b$	P' is the effective stress. A and b are fitting parameters. σ_{r} = 1kPa, is the reference stress.	Bender element	[12, 19]
EPS particle lightweight soil	$\begin{cases}G_{\max}=Ak^{n_1}F(e')\left(\sigma_0'\right)^{0.5}\\F(e')=(\eta_1-e')^2/(1+e')\end{cases}$	A is fitting parameter. k is the ratio of the unconfined compressive strength of lightweight soil to that of plain soil. $F(e')$ is a power function related to the void ratio of lightweight soil. σ_0' is effective confining pressure. e' is the relative void ratio of lightweight soil. n_1 and η_1 are fitting parameters related to the shape of the fitting curve.	Dynamic triaxial	[23]
EPS particle lightweight soil	$G_{\max}=AF(e)\mathrm{OCR}^n(\sigma_0')^{0.5}$	A and n are fitting parameters. OCR is over-consolidation ratio. σ_0' is effective confining pressure. $F(e)$ is a function related to the void ratio.	Dynamic triaxial	[24]
EPS composite soil	$G_{\max}=(m\sigma_{\mathrm{c}}+n)q_{\mathrm{ucs}}^{\beta}$	m, n and β are fitting parameters. q_{ucs} is unconfined compressive strength. σ_{c} is confining pressure.	Resonant column	[28]
Rubber−granular soil materials	$G_{\max}=180\times C_{\mathrm{u,s}}^{b}e_{\mathrm{eq}}^{x}\left(\dfrac{\sigma_{\mathrm{m}}'}{p_{\mathrm{a}}}\right)^{n_G}R_{\mathrm{G}}$	σ_{m}' is effective confining pressure. $C_{\mathrm{u,s}}$ is the non-uniformity coefficient of soil. e_{eq} is equivalent void ratio. R_{G} and n_{G} are the parameter that reflect the influence of the rubber content in the value of the $G_{\max}$. p_{a} is atmospheric pressure. b and x is the fitting parameter.	Resonant column, Dynamic triaxial	[29]
Rubber−granular soil materials	$G_{\max}=A\times\dfrac{(a-R)^2}{b+R}\times\sigma_3^n$	R is the void ratio of rubber−granular soil. σ_3 is confining pressure. A, a, b and n are fitting parameters.	Dynamic triaxial	[30]
Lightweight sand−mycelium soil	$G_{\max}=\alpha\beta^{W_{\mathrm{S}}}\left(\dfrac{\sigma_3'}{p_{\mathrm{a}}}\right)^k$	α and β are material constants associated with the substrate material content. k is the material constant in relation to the effective confining pressure. p_{a} is the standard atmospheric pressure. W_{S} is the substrate material content. σ_3' is effective confining pressure.	Dynamic triaxial	[31]

受固化剂影响轻质土阻尼作用机制与常规土体略有不同，轻质土阻尼机制可能包括：水泥水化产物水化硅酸钙（C–S–H）的材料阻尼，土颗粒或 EPS、橡胶颗粒的材料阻尼，C–S–H 与土颗粒或 EPS、橡胶颗粒接触的结构阻尼[21].

表 2 总结了轻质土动模量、阻尼比的主要影响因素及变化规律，已有研究初步揭示了配合比、应力状态和振动频率等因素对轻质土动模量、阻尼比的影响规律. 众多学者建立轻质土动剪切模量和阻尼比计算模型，如表 3 和表 4 所示，然而上述模型多针对 EPS 轻质土和橡胶轻质土，尚未有学者对泡沫轻质土动模量、阻尼比计算模型进行深入研究.

轻质土还可用作加筋土，Alaie 与 Chenari[42] 发现砂土中添加质量分数为 0.9% 的 EPS 颗粒即可使砂土−土工格栅界面循环剪切刚度降低 30% ~ 63%，阻尼比提高约 2 倍. 循环荷载作用下，EPS 轻质土−土工格栅界面峰值剪应力随 EPS 含量增加而下降，土体产生收缩变形，且收缩变形量随 EPS 含量增加而提高[43].

综上所述，现有研究分析了配合比（固化剂掺量、轻质材料含量、原料土掺量、含水率等）和应力条件（围压、波形、振动频率等）对轻质土动模量和阻尼比的影响. 然而主应力轴旋转、变围压等复杂应力状态以及干湿循环、冻融循环、硫酸盐侵蚀等环境因素对轻质土动力变形特性的影响规

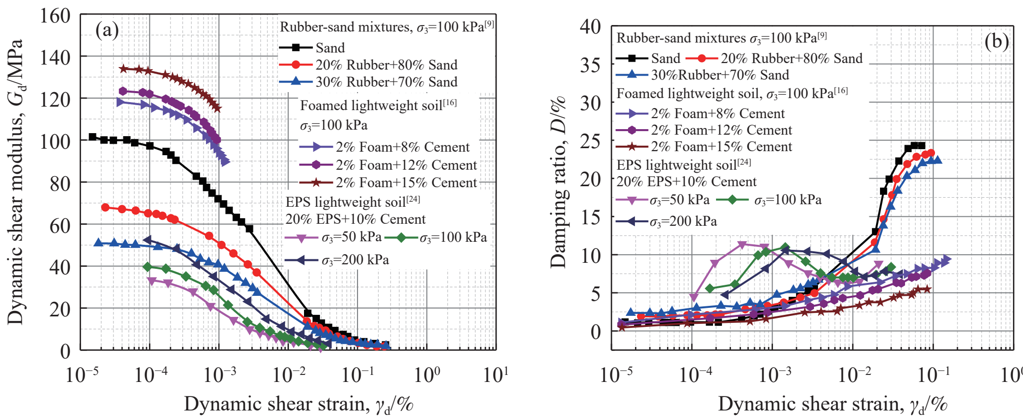

图 4 轻质土动剪切模量、阻尼比变化规律. (a) 动剪切模量; (b) 阻尼比[9, 16, 24]

Fig.4 Dynamic shear modulus and damping ratio of lightweight soil: (a) dynamic shear modulus; (b) damping ratio[9, 16, 24]

表 2 各因素对轻质土动模量、阻尼比影响

Table 2 Influence on the dynamic modulus and damping ratio of lightweight soil

Influencing factors (increment)	Main conclusions		Ref.
	Dynamic modulus	Damping ratio	
Dynamic stress amplitude	Increase first and then decrease or decrease	Increase	[33]
Dynamic axial strain	Decrease or first increase and then decrease	Increase or decrease first and then increase	[34]
Vibration times	Increase first then decreases	Increase	[33]
Confining pressure	Increase	Decrease	[35−36]
Initial consolidation stress ratio	Increase	Minor influence, no obvious regularity	[26]
EPS (rubber, foam) content	Increase first and then decrease or decrease	Decrease first and then increase or increase	[12, 35]
Density	Increase	Decrease	[37]
Water content	Decrease	Decrease first and then increase	[37]
Cement content	Increase	Decrease or minor influence	[38]
Curing age	Increase	Decrease	[39]
Vibration frequency	Increase	Increase	[39−40]
Intermediate principal stress coefficient	Minor influence	Minor influence or decrease	[26]
Direction of principal stress	Minor influence	Minor influence or decrease	[26]
Freezing temperature	Increment		[22]
Freeze-thaw cycles	Decrease		[21, 41]

律尚缺乏深入研究. 现有轻质土动剪切模量、阻尼比计算模型多基于土体动本构模型建立, 未考虑轻质土独特孔隙结构的影响, 循环荷载对轻质土微观孔隙结构的影响亦未有学者进行深入研究.

2 轻质土动强度特性试验

2.1 轻质土动强度分析

2.1.1 轻质土破坏标准选择

破坏标准的选择对研究轻质土动强度变化至关重要. 目前常用的破坏标准主要有应变标准、孔压标准、极限平衡标准和屈服标准, 由于 EPS 轻质土和泡沫轻质土内含有大量封闭气泡, 难以达到完全饱和状态, 故孔压标准和极限平衡标准并不适用[13]; 研究发现 EPS 轻质土和碱渣轻质土在加载过程中应变曲线未出现明显转折点, 使用屈服标准并不合理, 故常选择压应变达到 5% 或广义剪应变达到 6% 作为轻质土破坏标准[34, 44−46]; 王庶懋认为应以峰值压应变作为 EPS 混合轻质土破坏标准. 橡胶颗粒混合轻质土在动荷载作用下可能会产生液化现象, 故常以孔围压比达到 1.0(液化标准) 或动应变达到 5% 作为橡胶颗粒混合轻质土的破坏标准[47−48].

2.1.2 轻质土动强度变化规律

通过绘制试样达到相同破坏标准时的 τ_d–

表 3　轻质土动剪切模量衰减模型

Table 3　Attenuation model of the dynamic shear modulus of lightweight soil

Material type	Calculation model	Model parameters	Ref.	Remark
Rubber−sand mixtures	$\frac{G}{G_{\max}}=1-\left[\frac{(\gamma_a/\gamma_0)^{2B}}{1+(\gamma_a/\gamma_0)^{2B}}\right]^{A'}$	γ_a is the dynamic shear strain amplitude. γ_0, A' and B are soil test parameters.	[9, 18]	Based on Davidenkov's model
EPS composite soils	$\frac{G}{G_{\max}}=\frac{1}{1+(\gamma_a/\gamma_r)^{\xi}}$ $\gamma_r=0.506\times\left(\begin{array}{l}1.474\times(m_c/m_s)^{0.601}\\-0.068\times(V_E/V_S)^{1.115}\end{array}\right)\times\sigma_c^{0.113}-0.119$	γ_a is the dynamic shear strain amplitude. γ_r is the reference shear strain. ξ is soil test parameters. σ_c is confining pressure. m_s is the weight of dry soil. m_c is the weight of cement. V_E is the volume of EPS. V_S is the volume of the cemented soil .	[15, 28]	Based on Darendeli's model
EPS−sand mixtures, Rubber−sand mixture, fly ash bubbles mixed with light soil	$\frac{G}{G_{\max}}=\frac{1}{1+\gamma_a/\gamma_r}$	γ_a is the dynamic shear strain amplitude. γ_r is the reference shear strain.	[16, 25]	Based on the Hardin−Drnevich model
Rubber mixtures	$\frac{G}{G_{\max}}=\frac{1}{1+\left(A\times\sigma_3^n\times(1+R)^m\right)\times\gamma^p}$	*A, m, n* and *p* are fitting parameters. σ_3 is confining pressure. *R* is the mass ratio of granulated rubber. γ is the dynamic shear strain.	[30]	Based on the Hardin−Drnevich model

表 4　轻质土阻尼比计算模型

Table 4　Calculation model of the damping ratio of lightweight soil

Material type	Calculation model	Model parameters	Ref.	Remark
Rubber−sand mixtures	$\lambda=\lambda_{\min}+\lambda_0\left(1-\frac{G}{G_{\max}}\right)^{\beta}$	$\lambda_{\min}$ is the minimum damping ratio of lightweight soil. λ_0 and β are soil test parameters.	[9, 18]	
Fly ash bubbles mixed with light soil	$\lambda=\lambda_{\max}\left(1-\frac{G_d}{G_{\max}}\right)^{M}$	$\lambda_{\max}$ is the maximum damping ratio of lightweight soil. *M* is a fitting parameter.	[16]	
Rubber−sand mixtures	$\lambda-\lambda_{\min}=b\left(\frac{G}{G_{\max}}\right)\lambda_{M,c,r}R_c$	*b*, $\lambda_{M,c,r}$ and R_c are fitting parameters.	[17]	Based on Darendeli's model
EPS lightweight soil	$\lambda=\lambda_{\min}+\lambda_{\max}\left(1+k\gamma_d^n\right)^m$	$\lambda_{\min}$ and $\lambda_{\max}$ are the minimum and maximum damping ratios of lightweight soil. *k*, *m* and *n* are fitting parameters. γ_d is the dynamic shear strain.	[28]	Based on the gravel soil model proposed by Rollins

$\lg(N_f)$ 曲线或 R_f–$\lg(N_f)$ 曲线来反映土体动强度变化规律（τ_d 为试样 45°面上的动应力幅值，R_f 为动强度比，$\lg(N_f)$ 为破坏振次的对数形式），如图 5 所示轻质土动强度均随破坏振次的增加显著减小；湿密度（ρ）越大，轻质土动强度越高；当水泥含量为 91 kg·m^{-3} 时，EPS 质量分数（w_e）的增加使得轻质土动强度显著减小. 目前橡胶颗粒轻质土动强度特性的研究多关注其抗液化特性，橡胶颗粒的添加可显著提高其抗液化能力[49−50]. 此外，振动频率的减小、围压的提高均有利于提高橡胶轻质土的抗液化能力[51]，橡胶颗粒的尺寸和颗粒级配亦会对其液化强度产生显著影响[19].

EPS 轻质土和泡沫轻质土难以达到完全饱和状态，在振动荷载作用下不会产生液化现象，现有研究多关注其达到破坏标准时的动强度值. 围压、EPS 掺入比、密度、固化剂掺量、养护龄期、振动频率等均可影响轻质土动强度曲线[45, 51]. 王庶懋[46]发现 EPS 含量的增加使得砂土−EPS 混合轻质土动强度逐渐减小；Zhu 等[52]发现水泥质量分数低于 10% 时，EPS 掺量的增加会显著减小轻质土动

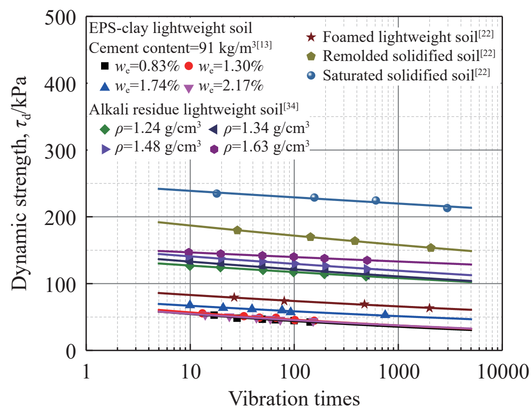

图 5　轻质土动强度曲线[13, 22, 34]

Fig.5　Dynamic strength curve of lightweight soil[13, 22, 34]

强度，当水泥质量分数大于 20%，轻质土强度始终大于黏土；黎冰[13]发现黏土−EPS 混合轻质土的动强度随 EPS 含量的增加先增大后减小，即存在最优 EPS 掺入比，可使黏土−EPS 混合轻质土动强度达到最大值；泡沫轻质土的动力性能表现出明显的密度依赖性[53]，随密度增大，其动强度显著提高，破坏模式由压缩破坏和剪切破坏向劈裂破坏发展[54].

固化剂掺量对轻质土动强度的影响主要与固化剂水化反应后产生的 C–S–H 有关, 随固化剂掺量的增加, 轻质土中 C–S–H 含量增多, 颗粒间胶结作用增强, 孔隙比减小, 故动强度显著提高[13, 46]. 泡沫轻质土的养护龄期对轻质土动强度的影响主要与水泥水化反应有关, 水泥水化反应速率在养护初期增长较快, 而后逐渐减缓, 养护 90 d 后水化反应基本完成, 故随养护龄期增加, 轻质土动强度逐渐增大直至趋于稳定[13, 46]. 黎冰[13]、钟晓凯[22]、杨少坤[34] 发现 EPS 轻质土和污泥固化轻质土动强度均随振动频率的增加而增大, 振动频率对轻质土动强度的影响主要与试样孔压、应变发展和蠕变效应有关.

杨少坤[34] 通过循环扭剪试验模拟交通荷载作用时主应力轴旋转对轻质土动强度的影响, 研究发现碱渣固化轻质土动强度随大主应力方向角的增大而降低; 当中主应力系数为 0.5 时, 动强度最大. 自然环境下的干湿交替、冻融循环会对轻质土动强度产生不利影响, 杨爱武等[27, 55]、钟晓凯[22] 发现干湿、冻融循环作用使得轻质土内部微观结构和胶结力被破坏, 致使轻质土动强度显著减小, 泡沫轻质土动强度随冻结温度的降低、冻融循环次数和干湿冻融循环耦合作用次数的增加而逐渐降低, 并最终趋于稳定.

2.1.3 轻质土动强度指标

可利用莫尔库伦强度理论, 通过绘制动强度包线的方法来确定土体动强度指标, 即动黏聚力 c_d 和动摩擦角 φ_d. 钟晓凯[22] 发现污泥固化轻质土的强度破坏包络线呈折线型, 这表明污泥固化轻质土具有明显的结构性. 此外, 水泥等固化剂的添加增强了轻质土的黏结力, 使其具备一定的抗拉强度, 故轻质土的莫尔圆可能会出现在第二象限中[13]; 已有研究表明, 由于水化物的胶结作用, 轻质土 c_d 和 φ_d 均随固化剂掺量和养护龄期的增加而增加[16]. 黎冰[13] 发现 EPS 含量的增加使得 EPS 混合轻质土的 φ_d 逐渐减小, c_d 则先增大后减小; 王冬容[16] 发现随 EPS 掺量或气泡含量的增加轻质土的 c_d 和 φ_d 均逐渐减小; c_d 变化规律的不同主要与试验参数的定义有关, 黎冰[13] 试验中随 EPS 掺入比的增大, 单位体积内水泥含量增加, 故 c_d 受到 EPS 颗粒掺入比和水泥含量耦合作用, 轻质材料的添加增大了颗粒间空隙, 使颗粒间接触面积减小、胶结作用减弱、水泥土骨架变脆弱, 而 EPS 颗粒和橡胶颗粒的增加亦使颗粒间 "润滑作用"增强, 故动强度指标随轻质材料掺量的增加而减小.

上述研究多关注材料配合比对轻质土动强度指标的影响, 加载频率、荷载类型、环境因素等对轻质土动强度指标的影响尚未有学者深入分析, 基于试验结果建立轻质土动强度指标计算模型对于轻质土的工程应用具有重要价值.

2.2 轻质土临界动应力及累积应变

当轻质土用作路基填料时, 在长期交通荷载作用下可能会产生疲劳破坏, Hou 等[44] 根据动应变累积变形速率, 将 EPS 轻质土动应变时程曲线分为振动压实、振动变形和振动破坏三个阶段. 当动应力幅值(σ_d)小于临界动应力时, 轻质土在较小振动次数后应变趋于稳定; 当动应力幅值趋近临界动应力时, 试样应变速率增大, 但累积应变最终仍会趋于稳定; 动应力幅值大于临界动应力后, 轻质土在有限振动次数下累积变形急剧增长, 发生脆性破坏[55]; 故工程中轻质土所受动应力应小于其临界动应力, 理论上同一土体在相同应力状态下的临界动应力为固定值, 但在室内试验中, 临界动应力通常在某范围内, 如图 6 所示, 污泥固化轻质土临界动应力在 300 ~ 350 kPa, 为工程安全考虑, 可取其下限值作为临界动应力.

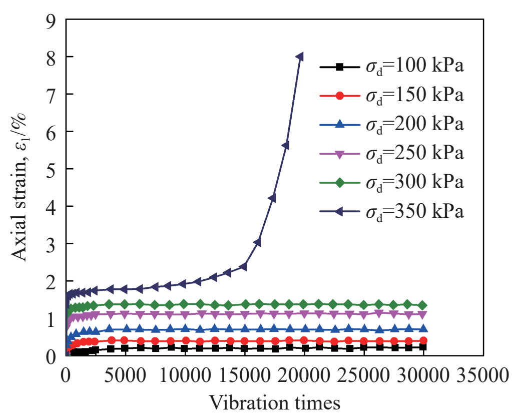

图 6 污泥固化轻质土累积变形曲线[58]

Fig.6 Cumulative deformation curve of solidified light soil[58]

王庶懋[46] 发现 EPS 轻质土临界动应力比随固结围压、EPS 含量的增加而减小, 随水泥掺量的增加而增大. Huang 等[56] 发现泡沫轻质土的临界动应力随密度的增加而增加, 风干泡沫轻质土的临界动应力略高于饱和轻质土. 随动应力幅值和振动次数的增加, 泡沫轻质土累积应变逐渐增大, 直至试样发生脆性破坏[57]. 杨爱武等[58] 发现污泥固化轻质土在循环荷载下的破坏过程可分为: 微裂纹出现阶段、裂纹扩展阶段和整体错动阶段, 干湿冻融循环会加剧轻质土结构损伤, 导致临界动应力减小, 累积应变增大. 杨少坤[34] 发现碱渣轻质土

的广义剪应变随密度和中主应力系数的增加及振动频率的减小而增大.

综上所述，轻质土在长期循环荷载下的塑性累积应变对轻质土路基的长期变形评估至关重要，探究影响轻质土疲劳寿命的显著因素和作用规律，以及轻质土疲劳裂纹扩展特性，提出考虑经济和耐久性的轻质土路基路面一体化设计方法，是轻质土路基广泛应用的关键.

3 轻质土工程应用

众多学者通过模型试验、现场测试、数值模拟等方法研究动荷载作用下轻质土动力响应. Alaie 等[59] 和 Gao 等[60] 通过振动台试验研究地震荷载对 EPS 轻质土动力响应的影响，研究发现 EPS 轻质土抗震性能良好，EPS 掺量的增加使得轻质土峰值加速度、动弹性模量和动应变显著减小，阻尼比迅速增大. Tafreshi 等[61] 通过室内模型试验研究橡胶颗粒轻质土作为管道回填土的动力响应，研究表明橡胶颗粒的添加可以有效保护管道免受疲劳破坏，并可有效减轻循环荷载作用下土体沉降变形、管道挠度变化和管道累积应变. 众多学者通过模型试验和现场测试，研究了泡沫轻质土用作铁路[62]、高铁无砟轨道[56]、扩宽公路[63]、路涵过渡段[64] 等路基填料时的动力特性，研究发现：(1)与传统水泥加固路基相比，泡沫轻质土在循环动态荷载下具有良好的长期动态稳定性，可显著减小路基压力和弹性位移，还可提高轨道刚度和铁路结构的耐久性；(2)泡沫轻质土用作高铁无砟轨道路基填料时需设置一定厚度的动态缓冲层；(3)地震荷载作用下，随振幅增加泡沫轻质土表现出滤波特性，路基内部应变表现出随相对高程先增加后减小的趋势.

蔡骁等[25] 提出在对交通荷载作用下 EPS 轻质土路基动力响应进行研究时应采用非线性动力本构模型，并考虑应力路径的影响. 数值模拟研究发现：(1)采用加筋泡沫轻质土填筑路基过渡段能有效减少结构振动[65]；(2)泡沫轻质土可吸收和分散应力波，轻质土路基中动应力、动位移和加速度均随路基深度的增加而衰减，基床表层范围内衰减速度最快[66]；(3)泡沫轻质土可有效减少路桥过渡段不均匀沉降引起的轨面弯折，且改善效果随密度提高逐渐增强[30]. Ma 等[5] 发现泡沫轻质土隔震性能良好，且密度越低、结构厚度越大，隔震效果越显著. Hao 等[67−68] 通过阻尼法测得泡沫轻质土结构的阻尼比为 0.059，发现孔隙率对泡沫轻质土抗震性能影响显著，孔隙率为 0.101 的泡沫轻质土可同时满足经济性和承载力要求.

上述研究表明轻质土具有良好的动力变形特性，可被广泛应用于管道回填、路基填筑、隧道隔震等岩土工程领域. 然而上述研究未充分考虑填筑方式、埋深、填筑厚度、轻质土类型等因素对轻质土动力特性的影响，应结合工程实际，通过模型试验、数值模拟相结合的方法，研究轻质土最优填筑方式，完善轻质土施工工艺.

4 结论与展望

轻质土是一种具有广阔应用前景的土工材料，本文系统总结了轻质土动力特性研究进展，现有研究表明材料配比是影响轻质土动力学性能的主要因素，水泥等固化剂的使用使轻质土具备更高的动剪切模量和动强度，而轻质土内部独特的孔隙结构则使其具有较高的阻尼比；模型试验和数值模拟结果验证了轻质土在实际工程中具有良好的动力稳定性和耐久性，因此轻质土可被广泛应用于路基填筑、管道回填、隧道隔震等工程. 然而目前关于轻质土动力特性研究仍存在一定局限性，以下问题有待深入研究：

(1) 研究主应力轴旋转、变围压等复杂应力路径下的轻质土动模量、阻尼比变化规律、动本构模型、疲劳寿命和疲劳裂纹扩展特性.

(2) 分析环境因素（如干湿交替、冻融循环、硫酸盐侵蚀等）与动荷载耦合作用下的轻质土力学性能，研究轻质土在多场耦合效应下的工作机理，探讨轻质土在极端环境下的工程应用潜力.

(3) 通过微观结构分析、单元体试验和宏观模型试验对轻质土动力特性进行多尺度研究，分析轻质土在循环荷载作用下的微观结构演化规律，包括孔隙结构变化、泡沫破碎、颗粒间相互作用等，建立轻质土微观组成-结构-动力学性能-工程应用的精确关联与调控.

(4) 研究轻质土耗能机制，通过优化材料配比、改进工艺等措施提高其耗能能力，充分发挥轻质土在减隔震工程中的应用潜力.

(5) 研发新型固废轻质土，并结合模型试验、数值模拟和现场测试等手段，探索轻质土在不同工程场景下的性能表现和适用性，完善轻质土施工工艺.

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